Water quality in two small forested catchments in the Warra LTER site, Tasmania: Source of colour and nutrient enrichment

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Statement

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university and to the best of the author's knowledge and belief the thesis contains no copy or paraphrase of material previously published or written by other persons except when due reference is made in the text of the thesis.

Sven Meyer

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Abstract

Variations in water quality occur with changes in land use such as timber harvesting and land clearing for agriculture, and through natural environmental variations including vegetation, slope and geology. Water quality is regularly monitored by Forestry Tasmania to ensure streams and creeks maintain a healthy aquatic ecosystem. This research was conducted to investigate the source of natural elevated concentrations of colour, turbidity and associated nutrients observed in the pristine forested catchment of Warra Creek. A second catchment, Crystal Creek, was also studied and the comparison between the two creeks was used to help understand the natural variations.

The primary objective of this study was to conduct a review of the naturally occurring environmental variables that affect water quality; and to evaluate the sources and ranges of concentrations of physical and chemical constituents expected in Tasmania waterways. A second objective was to investigate the reasons behind differences in water quality between the two pristine forested catchments; and to provide Forestry Tasmania with a range of guidelines to assess potential water degradation in the southern forest of Tasmania.

Water was collected and analysed for twenty physical and chemical parameters through three sampling projects, designed to encompass the range of flow and water quality conditions experienced throughout a typical year. Samples were taken on fortnightly visits, through a snapshot sampling regime and during two storm events. Results from these three projects indicated that the source of colour and associated nutrient enrichment in Warra Creek can be attributed to the headwaters of this catchment. This area of the catchment contains organic rich soils on south facing slight slopes with large amounts of decomposing organic matter and prolonged water contact time with this organic matter. Increases in flow in both Warra and Crystal Creeks caused a significant flushing of accumulated organic material from these catchments, resulting in degraded water quality. A variety of environmental differences were discovered between the two catchments, which may explain the significant differences in water quality found, especially during periods of low flow. The implications from this study for the management of water quality by Forestry Tasmania are discussed.

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Chapter 1: Introduction

1.1 Background

Measurement of the quality and quantity of water flowing from forested catchments has been the subject of many studies in Australia and overseas (Vertessy 1999; Doeg and Koehn 1990; Hornbeck and Bailey 1998). Detailed information on the quality and quantity of water flowing from undisturbed forested catchments, allows analysis of natural variation, provides a benchmark for comparison of different catchments and permits the evaluation of disturbance effects. It also provides useful information for the study of aquatic ecosystems within the catchment, such as stream health and biodiversity.

Elevated nutrient concentrations are often cited as contributing to unwanted plant growth and associated water quality problems. As a result, several programs, reports and publications have been produced towards developing nutrient criteria or guidelines for inland waters (e.g. ANZECC 1996; CEAH 1997 and NHMRC 2000). However, these guidelines do not acknowledge the individuality of particular water bodies and are only useful for broad ranges of values covering the majority of situations. For nutrients and chemicals, either estimation of total loads, or absolute concentrations, are used to determine the nutrient status of water bodies. Tiller and Newall (1995) describe concentrations as providing a measure of the immediate availability of nutrients to algae and other plants, whilst nutrient loads are more applicable to an endpoint, such as a lake or dam. To determine if a particular creek or river has elevated nutrients and chemicals, measurements of these parameters need to be compared to similar catchments with no anthropogenic impacts.

Variations in water quality and quantity of water bodies occur after changes to land use, such as harvesting for timber and subsequent reforestation (Mackay and Cornish 1982). Codes of practise for forest operation in Tasmania have been put into place to protect water quality and flow on a catchment basis (Forest Practices Board 2000). Water quality and quantity information therefore needs to be regularly monitored in areas of forest operations, to ensure the codes of practise are being followed correctly and are working to maintain healthy aquatic ecosystems.

In order to collect information on water quantity and quality, a major hydrology research project has been established by Forestry Tasmania within the Warra Long-Term Ecological Research (LTER) site, near Geeveston in southern Tasmania (Ringrose and Meyer 2001). This hydrology project encompasses three discrete sub-projects, which are interrelated but operate over varying time frames. The three projects are: characterisation of a pristine stream; determination of the effects of commercial logging on stream hydrology; and the broad scale water sampling of the Warra LTER site. The main aims are: to provide reference data on the flow and physical characteristics of a small undisturbed stream (Warra Creek); to determine the hydrological effects of forest logging as specified by the Tasmanian Forest Practises Code; and to provide information on the physical water quality of the major rivers and streams within the Warra LTER site (Ringrose et al. 2001).

The "pristine stream" being used as a control for the hydrology project, is unusual in that it has poorer water quality than is normally associated with untouched catchments in the southern forests of Tasmania (Meyer et al. 2002a). This pristine stream, known as Warra Creek, has a distinctive brown water colour, with moderately high turbidity levels averaging 11.5 NTU (Ringrose et al. 2001), and develops large algae growths in periods of low flow. In comparison, nearby Crystal Creek is extremely clean, with little algae growth, very low turbidity and no colouration at baseflow levels. It, therefore, appears as though some natural environmental variations are affecting the water quality of Warra Creek, especially considering that Crystal Creek's lower catchment was logged and regenerated only nine years ago. Both streams drain from the Tasmania Wilderness World Heritage Area around Mount Frederick and Mount Weld and have similar geology, soils and vegetation.

In Tasmania, there is a clear trend of an east-west gradient in lakes, as a result of climate, gradient, soils and associated vegetation. This gradient consists of ionic compositions in the south-west and west lakes that are similar to dilute seawater, whilst ionic composition are similar to average freshwater composition in the east (Tyler 1992). The Warra LTER site sits squarely in the middle of the transition between east and west ionic compositions. As such, in depth analysis of the sources of nutrients from two apparently similar streams will help provide an explanation of the effect environmental variations have on ionic composition.

1.2 Project hypothesis, aims and objectives

The sources of relatively high turbidity, colour and associated nutrient enrichment in Warra Creek, posses an important research question that needs to be addressed. The following hypothesis will be examined in this thesis:

"The difference in water quality between Warra and Crystal creeks is due to a much greater contact time between water and organic matter in Warra Creek catchment."

This project aims to investigate the source of colour and apparent nutrient enrichment in the pristine forested catchment of Warra Creek. Crystal Creek catchment was also investigated with water quality results providing a comparative measure with which to evaluate degrees of natural water variation found in the southern forests of Tasmania. This analysis of water from two different catchments in the Warra LTER site can be utilised as a guide for the monitoring of potential impacts caused by forest harvesting in the southern forests of Tasmania and to provide baseline information for studies on aquatic ecosystems.

The objectives of this study are to:

1. conduct a review on the effects of flow, climate, vegetation, geology, fire history, aspect, slope and soils on water quality variations;
2. review the source and characteristics of major water constituents used for the assessment of catchment health, and determine expected concentrations within Tasmanian waterways;
3. investigate the reasons behind differences in water quality within the two creeks; and
4. provide Forestry Tasmania with a range of parameter levels to assess potential water quality degradation in the southern forests of Tasmania.

To address the aim and objectives of the study, water quality was examined at several different baseflow conditions and during autumn and winter storm events, in both Warra and Crystal creeks. In addition, Warra Creeks water quality was investigated at five locations that extend from downstream to the upper tributaries near the headwaters of the catchment. Samples were analysed for various physical

and chemical parameters, to identify any contamination point sources, or a general degradation of water quality throughout the Warra catchment.

1.3 Research approach

The development, approach and design of this study were a direct result of research conducted by the author on the Warra LTER project. In June of 1999 the author was employed as the Water Research Project Officer in the Division of Forest Research and Development, Forestry Tasmania. This job involved establishing continuous water monitoring equipment on three constructed weirs and the collection of routine water quality information from thirteen other streams in the Warra LTER region. Analysis of data over two years quickly led to the conclusion that the pristine catchment of Warra Creek has unusual water quality characteristics that needed to be evaluated before comparisons with other streams could be conducted.

Information on the monitoring of water quality from the southern forests conducted by the author includes several reports and publications (Meyer and Lynch 1999; Meyer et al. 2002a; Meyer et al. 2002b; Ringrose and Meyer 2001; Ringrose et al. 2001). Collectively this experience has provided the author with a broad knowledge base on the water quality of the region, the necessary skills to design and establish new monitoring experiments and a variety of different techniques with which to collect water samples.

Data collection and analysis utilised a variety of commonly accepted techniques. Water samples were collected over three different situations, designed to encompass the range of flow and water quality conditions experienced throughout a typical year. Samples were taken on fortnightly visits, through a snapshot sampling regime and during two storm events. Analysis of data was undertaken using bar graphs, box and whisker plots and by Pearson product correlations. Details of the methodology are presented in Chapter four.

The locations of these Warra and Crystal Creek are within what is known as the Warra (LTER) site, composing 15 900 hectare between the Huon and Weld Rivers, approximately 60 kilometres west, south-west of Hobart, Tasmania. The western

portion of the site is part of the Tasmanian Wilderness World Heritage Area and is managed for conservation values by the Department of Primary Industries, Water and Environment. The eastern portion is State forest managed by Forestry Tasmania for multiple use, including sustainable timber harvesting (Brown et al. 2002).

The wet *Eucalyptus obliqua* forests in southern Tasmania are managed on an rotation of 100 years for the production of sawlogs, veneer logs and pulpwood and to maintain sustainability, biodiversity and conservation values (Meyer et al. 2002b). Warra LTER was established to conduct ecological research and monitoring to assist in achieving these goals of sustainable forest management (SFM), as recognised by the 1992 Australian Government National Forest Policy Statement. The LTER site is dedicated to multi-disciplinary, long-term, site based research and is linked to an existing network of national and international LTER sites (Brown et al. 2002). Further information on the broader aspects associated with Warra LTER research and management is available in Brown et al. 2002.

1.4 Limitations of the study

The terrain associated with pristine forests in southern Tasmania is generally inaccessible without some type of road or track network. The Warra LTER site offers access to the base of the creeks studied and some limited walking tracks developed purely for the undertaking of scientific research. Access to Warra Creek was relatively good, with tracks at the base and near the upper portion of the catchment. From these tracks, others were cut to access the remainder of the catchment for water collection. However the top third of the catchment could not be accessed and no portion of Crystal Creek catchment can be accessed without considerable work in the construction of tracks.

The climate of Warra LTER is generally cold and wet, which is good for the development of large storms but can cause difficulties in the collection of water samples. The major problem found was difficulty with access, due to snow during the highest rainfall events in winter.

Other limitations relate to high cost of analysis for water and soil samples and the timing of sample collections due to work and time constraints.

1.5 Thesis outline

This thesis is divided into ten chapters. Chapter 1 has introduced the study, discussed the need for the information, stated the aims and objectives and outlined the limitations. Chapters 2 and 3 are literature reviews that discuss reasons for water quality variations and characteristics of parameters measured to determine the health of waterways. Chapter 4 details the methodology used in the study. Chapter 5 outlines Warra and Crystal catchments, their location, geology, vegetation, soils, topography and fire history. Chapter 6 discusses a soil survey that led to the classification of soil types for Warra Creek catchment. Chapter 7 details the results of the fortnightly water sampling program. Chapter 8 details the catchment snapshot water sampling results. Chapter 9 details the stormflow water sampling results. Chapter 10 provides a detailed discussion of the results and relates the findings to the provision of water quality guidelines for Forestry Tasmania in the southern forest.

Chapter 2: Factors affecting water quality

2.1 Introduction

The impacts of water flow, geology, soils, climatic conditions, vegetation and biological processes on water characteristics in forested catchments are reviewed in this chapter. The source and characteristics of major water constituents used to determine water quality of a particular water body are also outlined.

Chemical composition of drainage waters from small pristine headwater forested catchments has been widely studied in Australia, the United Kingdom, the United States and Europe (Day et al. 1999; Muscutt et al. 1990; Hornbeck and Bailey 1998; Hongve 1999). A range of important physical, chemical and biological processes that act within catchments to determine the composition of their drainage waters have emerged. These include:

1 the geochemical processes occurring through ion exchange, absorption and weathering;
2. the soil-water pathways determining the particular geochemical processes involved;
3. the physical processes of erosion and gas exchange;
4. the biological processes of uptake, respiration, decomposition, mineralisation and microbial-mediated oxidation and reduction; and
5. the hydroclimatic conditions of the catchment.

The sum total of these interactions present at a given time is thought to determine the chemical composition of drainage waters (Church 1997; Vogt and Muniz 1997). These interactions and processes are outlined in Chapter 2 and 3.

2.2 Water flow and discharge

The hydrological cycle represents the water balance between the land, oceans and the atmosphere. Precipitation falls directly on the ground, evaporates or is intercepted by leaves, branches and trunks of vegetation. Water that reaches the ground is absorbed

by leaf litter, stored in depressions or cracks or if the soil is saturated, flows overland. Water also filters into the upper layer of soil, at a rate that depends on the soil's characteristics and the amount of water already in the soil (STEU 1996).

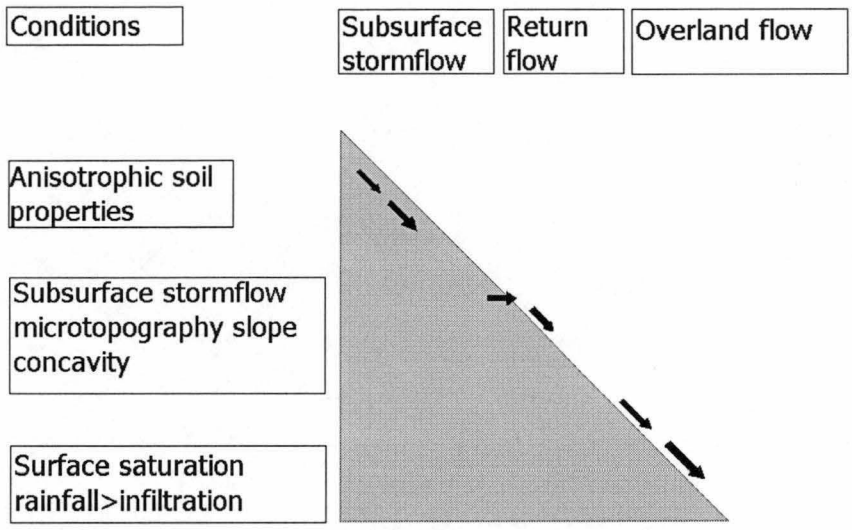
A key factor in determining the chemical composition of water that flows through a catchment, lies in the products and associated process encountered during its passage through the forest. Forest canopy and understorey plants, plant stems, litter and organic soil layers, mineral layers of soil, coarse tills and bedrock as well as some macro and micro biota, will alter composition of the water (Church 1997). Water composition is also dependent on the amount of groundwater already present, the hydroclimatic conditions of the catchment and the amount of precipitation.

In 1930, Robert E. Horton outlined the process of infiltration and overland flow, which became known as the Horton Model (Chapman 1996). The Horton model states that surface runoff begins as soon as the rate of precipitation exceeds the rate of infiltration. The principle point was that in a small catchment, all parts of the drainage area have essentially the same infiltration rates and therefore all parts contribute to surface runoff. This effectively means that the further a point is downhill, the larger the contributing drainage area and therefore the greater the depth of flow at that site.

However, a more complex model that is more relevant to forested catchments was produced by a group of forest hydrologists from the United States Forest Service (Chapman 1996). This model is predicated on the assumption that the area within a drainage basin that contributes surface-flow water changes, depending on hydroclimatic conditions. These hydrologists observed that only a small part of a basin area very near the water channel contributed to surface run-off. The rest of the basin further away made no contribution unless extreme rainfall events occurred.

Elsenbeer (2001) expanded the forest hydrologist model to describe conditions activating flowpaths in response to given events (Figure 2.1). The three flowpaths found in forested catchments are subsurface stormflow, return flow and overland flow. The circumstances under which subsurface stormflow turns into return flow are correlated to biological activity in the soil, changes in soil depth or slope gradient.

Figure 2.1: Conditions that activate a water flowpath in response to given events.



Source: (Elsenbeer 2001)

According to the Elsenbeer model the upper headwater areas of the catchment remain relatively moist even between storms. These areas constitute the only part of the total drainage basin that contributes water to the storm hydrograph, (i.e., all rainfall in such an area begins flowing immediately as the soil quickly reaches saturation capacity). These moist zones are often identified by the production of coloured waters. This is because the local water table is near the surface and capillarity provides water to the near surface soil. As rain persists, the percentage of the catchment contributing to surface runoff increases. However, this water does not contribute to the storm hydrograph, as infiltration rates occur over a longer timeframe. Rainwater from storms instead recharges the stored groundwater supplies (Church 1997; Leopold 1997).

Due to the complexities involved in determining which flowpath is contributing to what proportion of the river discharge, most catchments are characterised by base flow or base discharge. This is the minimum amount of water moving within the individual river system, and in most cases, is controlled by subsurface discharge.

Groundwater systems contain underground water that may move through the pores of rock or soil material, and through cracks or joints of rocks. The water sinks until it reaches a depth where the rock is impermeable and watertight and will collect above this impermeable layer, forming a saturated zone or water table. This water table

rises and sinks depending on the hydroclimatic condition of the catchment. The water table rises until it is exposed in the bottom of the deepest notch or depression in the area. This is known as a stream channel, whereby water from the channel flows downstream into deeper cut river channels. In dry conditions, the small channels are dry between rains and only the larger, deeply cut river channels carry water all year round (Leopold 1997).

Water flows downhill towards the lowest point, where it emerges in stream channels. However, if the surface is flat, water will not move, causing the production of soaks or lakes. When rain falls, water will seep downward towards the water table, causing increased flow in stream channels in wet conditions. After the rain has ceased, groundwater continues to flow towards the stream channels, until the subsurface water flattens out again (Leopold 1997).

Groundwater discharge is sampled under low flow conditions where water quality can be expected to be worse from the point of view of concentrations of some chemical and physical water parameters. Nethertheless, high flow conditions are responsible for moving the vast majority of a material downstream, albeit under lower concentrations (Fuller 1993). Water quality data therefore represent the situation at the time of sampling and do not necessarily reflect the past or future conditions of the stream.

Knowing the amount of discharge within a particular river is therefore very important because it can characterise the origin of many water quantity parameters. The composition of water quality is dependent on the hydrological regime of the river, (i.e., the amount of floods per year and their intensity). However, during flood periods, stream water contains surface water, sub-surface water and groundwater discharge. All three types of water are important to monitor as they have different water chemistral characteristics that affect the water quality of the catchment. Subsurface runoff is water that has circulated within the soil layer, leaching dissolved organic carbon and nutrients (nitrogen and phosphorus) from soils. Surface runoff is usually highly turbid and carries large amounts of total suspended solids, including particulate organic carbon. Groundwater carries most of the elements resulting from rock weathering (Chapman 1996).

The importance of knowing the river discharge rate has been highlighted during hydrochemical studies. Mulder et al. (1995), Leopold, (1997) and Vogt and Muniz (1997) revealed that low-flow streamwater was dominated by groundwater, relatively rich in base cations from the weathering of rocks. In contrast, high flow largely originated in their catchment-specific acidic soil horizon on the hill slopes at a greater distance from the stream.

Streamwater chemistry is therefore assumed to be a mixture of the two types (groundwater and near-surface runoff) of soil water. Groundwater (baseflow) is dominated by water from the upper bog layers, while near-surface (stormflow) water originates from the upper, more acidic soil zones (Bg-soil horizon) (Leopold 1997). This highflow resembles precipitation in terms of ionic strength and chemical composition, while baseflow is more concentrated due to weathering and evapotranspiration.

2.2.1 Stormflow characteristics

Several studies (Bowles et al. 1986; Campbell and Doeg 1989; Finlayson and Wong 1982; Vogt and Muniz 1997) have shown that storm-water runoff produces well defined peaks in the concentration of suspended solids. Most storms show a hystersis typical of sediment exhaustion, where the peak of concentrations occurs on the rising limb of the hydrograph and then declines even though discharge remains at a high level. Between storms, organic and inorganic material is prepared for transport within the zone of generation of quick flow by weathering processes, animal activity and litter fall, and is transported away by the first flush of quick flow. However, once the available supply of suspended solids is exhausted, concentration declines even though discharge may continue to rise. The overwhelming majority of sediment is therefore transported in streams during the initial periods of high flow (Campbell and Doeg 1989).

A study by Vogt and Muniz (1997) found that the intensity of leaching and accumulation is enhanced by increased hydrological residence time. Dry periods cause enhanced residence time and therefore increased leaching rates until the first runoff episode. The initial phases of storms often reach high total organic carbon

(TOC) levels, due to a washout of accumulated soluble organic matter from the catchment. However, during following rain episodes TOC is often lower despite greater runoff intensities.

Buffam et al. (2001) conducted a study looking at the patterns of dissolved organic carbon (DOC) and nitrogen (DON) delivery, compared between times of stormflow and baseflow in Paine Run, an Appalacian stream in the Shenandoah National Park, Virginia, USA. DOC and DON were found to be consistently low during baseflow and did not show a seasonal pattern. However, during storms, mean DOC and DON concentrations approximately doubled, with maximum concentrations occurring on the rising limb of storm hydrographs. The rapid response of DON concentrations to changes in flow suggested a near-stream or in-stream source of DON during storms. Paine Run showed a significant increase in DON during storms in conjunction with DOC. However, when a second storm occurred directly after the first storm, DOC and DON concentrations were all considerably lower. This suggests a flushing out of soluble DON from the respective source reservoirs.

The most important processes controlling dissolved organic matter (DOM) delivery to the stream during storms are near-stream or in-stream processes. Near stream sources include direct throughfall, saturated overland flow, and the flushing of upper soil layers in the riparian zone. Leachate of leaf litter and other particulate organic matter in the stream also contribute to DOM at all times, but especially during storms. The source reservoirs of DOM during the rising limb of a storm are therefore highly mobile surface runoff sources. Intermediate DOM soilwater sources occur during and immediately following runoff events, while a constant low DOM groundwater source is present during low flow periods.

No thorough studies have been conducted using water analysis through storm events in Tasmanian forested streams. However, Buckney (1974) and King and Tyler (1978) sampled rivers at a range of flow levels. In several rivers, rises of river flow were often accompanied by reduction of pH, increase of colour, a stoichiometric displacement towards seawater and increases in the concentrations of many nutrients.

2.3 Geology and soils

The volume of groundwater contained in the rock depends on the percentage of pores within a given volume of rock, known as porosity. The higher the porosity the more stored water present. Under the influence of gravity, stored groundwater drains from the pores, so when slope increases the contact time between water and substrate can decrease (Buckney 1971). Chapman (1996) describes how as this rain falls, water infiltrates the soil and roots of plants and moves into the rock nearest to the ground surface.

Groundwater occurs in association with geological materials, resulting in higher concentrations of dissolved salts, relative to surface water. Emmett et al. (1994), Hornbeck and Bailey (1998), Reinson (1976) and Rice and Bricker (1995) studied waters draining from a range of rock types. Their studies found that the chemical weathering rate of the underlying bedrock was the controlling factor in base cation rates. Concentrations of these constituents derived from rock weathering increased in streamwater during summer when the water table was below the regolith-bedrock interface and when streamwater consisted primarily of groundwater sources. These alkaline groundwaters were rich in calcium, magnesium and silica, and difference between catchments most likely reflected differences in the type of parental rock material and degree of weathering.

The composition and structure of the sub-soil are also directly affected by the nature of the parental rock type. In turn the type of soil present can make large differences to the water chemistry composition.

Nelsen et al. (1990) demonstrated that clay soils are used as a store for organic matter. Greater stores of organic matter were found in areas containing high clay content, resulting in high levels of retained organic matter, which are slowly decomposed by microorganisms. The clay content of soils is high when the parent material consists of basic rock with high weatherable mineral content (e.g. basalt or dolomite) opposed to acidic rocks with a low weatherable mineral content (e.g. quartzite or sandstone). Areas with sandy soils (low clay content) and a rainfall of more that 700 millimetres give rise to waters with high dissolved organic matter (DOC) (Oades, 1982).

In Tasmania, it was found that dystrophic lakes (high in concentrations of DOC) tended to occur in quartzite areas, whereas oligotrophic lakes (low DOC) tended to occur in areas of Jurassic dolerite (Bowling et al. 1986). Dolerite is a basic rock that would readily give rise to the formation of clay, whereas soils formed from quartzite could be expected to be sandy. However, the path of water through the soil is also important in determining stream DOC concentrations (Nelson et al. 1990).

Tarvydas (1978) conducted soil surveys of large tracts of land in western Tasmania, as part of the Lower Gordon River scientific survey. The soil survey revealed that the southwestern parts of Tasmania are covered by soils derived from the decay of vegetation. These organic soils or peats cover all geological types and are found under a variety of vegetation types including scrub, heath, mixed forest and rainforest (Pemberton 1989).

Organic soils are not directly related to the underlying soils and can develop over bedrock, gravel layers, sand, clay substrates or over deeper mineral soils. Peat formation is promoted in areas of high rainfall (> 750 millimetres per annum), low temperatures, low evaporation and high relative humidity (Pemberton 1989). These soils are rich in plant remains, with at least 20 per cent organic matter in the top 30 centimetres of the soil.

Two types of peat can occur, depending on their internal drainage patterns. In well-drained profiles, usually on slopes or in elevated flat positions a reddish-brown soft fibrous peat develops. However, on flat, waterlogged areas, a grey muck peat develops. The tallest and densest forests are confined to areas of fibrous peat, with roots not developing past the peat horizon. In areas of muck peat, the vegetation is greatly reduced in size and forests tend not to develop (Tarvydas 1978).

Pemberton (1989) classified the organic soils into specific types. One important type is found on well drained slopes and ridges. This organic soil is often on well-drained terrain such as undulating plains, ridges and slopes up to 700 metres, and is common on exposed westerly aspects. This soil varies in colour from reddish brown in better-drained locations to brown and black in poorer drained locations. Vegetation found on these well drained slopes includes; *Gymnoschoenus sphaerocephalus, Melaleuca squarrosa, Melaleuca squamea, Leptospermum nitidum, Leptospermum scoparium,*

Baurea rubiodes, Banksia marginata, and *Baloskian tetrophyllum.* Thickets of *Eucalyptus nitida* occur on some slopes in patches where the underlying mineral soil is deeper.

Swaine et al. (1993) found that in small southern Tasmanian streams the initial winter period of high rainfall resulted in the streams becoming a deep tan colour. This was attributed to the leaching of the tannins and nutrients that had accumulated in the soil from litter decomposition during the summer period. This process also abruptly increased stream acidity and conductivity. Hongve (1999) and Hongve et al. (2000) discovered that during the summer under humid conditions the material is processed by organisms on the forest floor, resulting in DOC leaching from peat being highest during late summer months, producing more coloured runoff at higher temperatures, and declined rapidly thereafter.

2.4 Atmospheric factors

Buckney and Tyler (1973) studied a variety of Tasmanian waterways and concluded that climate was a more important determinant in the variability of total chemical concentrations in water, than geology. This study analysed 150 Tasmanian water systems and made the assumptions that climate controlled precipitation, temperature, evaporation rates and the atmospheric supply of salt to the water bodies.

The Warra LTER site, in the south-west of Tasmania is in the direct path of a predominantly westerly air flow, known as the Roaring Forties. These rain-bearing winds experience orographic uplift and drop diluted seawater of moderate salinity onto the west and south-west coasts of Tasmania (Buckney and Tyler 1973b). Most of the waters in south-west Tasmania are good examples of precipitation dominance waters, with major ions supplied by atmospheric precipitation resulting in waters with ionic dominance orders and ionic proportions similar to those of seawater (Buckney and Tyler 1973b). Such waters are frequently found in areas in the path of maritime winds. Concentrations are therefore proportional to their distance from the sea.

Buckley and Tyler (1973b) sampled a large range of inland Tasmanian waters and found that the majority (89.4 per cent) of waters has seawater ionic compositions or moderate geochemical modifications. Geochemical enrichment principally occurs through calcium and magnesium bicarbonates causing a dominance of sodium to be replaced by either calcium or magnesium. Most of Tasmania's waters were therefore categorised as intermediate between precipitation and rock dominance.

Climate also plays a major role in the temperature of stream-water. Water bodies undergo temperature variations along with normal climatic fluctuations, although with a substantial time lag (Fuller 1993; Chapman 1996). The temperature of surface waters is influenced by season, air circulation, cloud cover, latitude, altitude, vegetation cover and flow and depth of water (Chapman 1996; STEU 1996). The regulation of water and soil temperature is important as they impact on the biological processes of uptake, respiration, decomposition, mineralisation and microbio-mediated oxidation and reduction.

2.5 Vegetation and associated biological processes

Where surface waters are not directly related to seawater ionic compositions or a moderate geochemical enrichment, biological, topographical and temporal variations are likely to be responsible for any deviation from normal nutrient levels (Buckney 1971). The type of vegetation present can play a major role in determining the water quality within a catchment. Comparisons of input-output budgets in paired catchments in the Mont Lozere region of France show the specific effect of vegetation types on soil dynamic and the biochemistry functioning of the ecosystems. Leflong et al. (1990) (pp 143) demonstrated that the vegetation type within a catchment determined three features:

1. the water budget, and therefore the drainage intensity;
2. the capturing ability for atmospheric deposition; and
3. the nature and intensity of internal soil processes of acidification, humidification, and bicarbonate production and nitrogen species transformation.

Vegetation in the form of forests can therefore have varying effects on stream nutrients. Norton and Fisher (2000) examined the effects of forests on stream water quality by comparing two large similar catchments, Choptank and Chester Basins (North America). It was discovered that forests in the Chester Basin had a positive effect on water quality by acting as a sediment trap, consuming and storing nutrients by accreting biomass, stimulating microbial assimilation of nutrients in forest soils and providing an environment conducive to microbial dissimilation of nitrate to ammonia. However, it must be noted that Chester Basin has high stream slopes, fine textured soils and a high runoff potential.

Bowman et al. (1986) confirms this relationship between type of vegetation present and water quality. Bowman et al. (1986) surveyed 14 south-west Tasmanian sedgeland-heaths and found no clear relationship between rock type and soil fertility, but there was evidence of soil-vegetation interactions. Over vegetation transition from sedgeland to forests on uniform geology a change in soil type occurred. Forest has more fertile soils and a higher concentration of nutrients in above ground biomass, than the adjacent sedgeland-heaths. Soil organic matter was found to be related to water content, total nitrogen, total and exchangeable sodium, calcium and magnesium. However, total and available phosphorus, total potassium and iron were found to be independent of organic content.

Boughton (1970) emphasises the problems associated with vegetation and the hydrologic conditions of a catchment. It was noted that in areas of high rainfall, slight slopes and little destruction of forest litter by fires, decaying vegetation can contaminate the water supply in a number of ways including increased oxygen demand, resulting in a depletion of aquatic life and a raising of acidity and colour levels. Boughton (1970) placed the rivers of Tasmania into this category. Concentrations of major ions in waters in the south-west are however low, in spite of the vast decaying vegetation often present in the catchments (Buckney and Tyler 1973b). This is because the rocks within the catchments are Precambrian quartzites, schists and related metamorphics and are largely resistant to chemical weathering (Banks 1965). The above generalisation does not however apply to areas that lie within the Jurassic dolerite region of south-west Tasmania (Steane and Tyler 1978).

Rainwater reaching the forest canopy may either strike tree crowns and understorey vegetation or pass directly to the litter layer. When rainfall flows over the surface of vegetation, it usually shows a net gain in content of many chemical elements. This gain results from the leaching of elements derived from plant tissues. The passage of rainwater through the crowns of eucalypt forests gains its greatest enrichment in sodium, chloride, potassium and calcium (Raison and Khanna 1982). This leaching is more intense at the beginning of the rain period, ion concentration thus decreases with increasing amounts of rain.

Hongve et al. (2000) demonstrated that rainfall passing through leaf litter on the forest floor contributed the major percentage of dissolved substances in soil and surface water. Graynorth (1979), Raison and Khanna (1982) and Swain et al. (1993) also noted that litter leachates are often a dark colour, reflecting a high content of soluble and colloidal organic carbon and nutrients. Raison et al. (1982) established that the composition of litter leachate depends on many factors, including the chemical composition of precipitation throughfall, nature and rate of ion mobilisation during litter decomposition, the time since last rain event, and the amount of rainfall.

Leaching from litter on the soil surface is often the primary source of dissolved carbon, especially when leached by autumn rain. Hongve et al. (2000) demonstrated that leaching of fresh litter is a significant source of several inorganic nutrients. Litter production is abundant in all forested catchments, whatever the amount of soil and soil type. The leaching of litter can therefore explain why highly coloured lakes are found in catchments without swamps (Hongve, et al. 2000). However, even though water percolating through litter is considerably enriched in DOC, it is the water pathways that will determine the amount of DOC in streams (Hongve 1999).

Hongve (1999) examined the production of dissolved organic carbon in forested catchments and found that concentrations of coloured dissolved organic carbon in streams and lakes draining forested catchments vary within wide limits. High DOC concentrations are usually associated with catchments containing a high percentage of mires with coloured DOC in surface water thought to be derived from peat and organic soils. However, many coloured lakes are also found in catchments without wet areas. A marked seasonality in the concentration and character of DOC in discharge from forested catchments has been reported, with autumn runoff events

often giving significant DOC concentration peaks (Ivarsson and Jansson 1994). In forested catchments however the main production of DOC takes place on the forest floor with leaf litter being an important source of colour in runoff and soil water (Malcolm 1985).

In 1999, Hongve conducted a study aimed at identifing the major sources, other than mires for DOC in forested catchments. It was demonstrated that different tree species yielded different concentrations of DOC and colour. Fresh litter from deciduous trees produced high DOC and colour values during autumn, with concentrations declining with time. Water colour from 86 lakes in Norway (inland climate) and 414 lakes in countries along the western Atlantic coast (coastal climate) was examined. No significant relationship in inland lakes between watercolour and percentage of mires in the catchment ($r^2 = 0.008$, $P > 0.1$) was found. For the coastal lakes there was a weak but significant increase in water colour with increasing percentage of mires ($r^2 = 0.099$, $P < 0.001$). The results showed that fresh deciduous litter has a very high potential for production of DOC in the short term (Hongve 1999). In contrast to what may be a common view of coloured waters, the influence of mires on the water's content was found to be insignificant.

The influence of litter leachate on water quality was examined in the Warra LTER site in Tasmania by Swaine et al. (1993). Swaine et al. (1993) noted that litter fall varied between streams due to differences in floristic composition and density of the canopy. Although peak rates varied, they were greatest during the summer period and smallest during August to September. The atypical species was *Nothofagus cunnninghamii* that contributed to the litter in Warra Creek. At this site, peak rates were apparent from autumn to mid-winter. Therefore, wherever *Nothofagus cunninghamii* are present its leaves tend to be the dominant material in natural leaf packs during winter.

The creeks of the southern forests of Tasmania receive a majority of their annual litter fall in summer; this litter is composed of *Eucryphia lucida*, *Eucalyptus obliqua* (leaves and bark), *Athrosperma moschatum* and *Pomaderris elliptica* leaves. During autumn, the litter consists *of Nothofagus cunninghamii*, together with eucalypt bark and branches (Swaine et al. 1993). The majority of leaf fall occurs during the highest water temperatures and lowest water flow, with a smaller autumn/winter pulse. The

significance of this, in terms of water quality and nutrient value, is important. Spring and early summer inputs contain high amounts of nutrient rich pollen, flower parts and insect parts. In mid to late summer, the peak litter inputs consist of a mixture of slow decomposing material (bark and branches) and a majority of fast decomposing leaves. During the autumn and winter period the streams receive a continuous litter input of slow decomposing *Nothofagus cunninghamii* in the rainforest, and bark and branches in the eucalypt dominated forest (Swaine et al. 1993).

Swaine et al. (1993) concluded that the introduction of allochthonous material into the upper reaches of a stream represents the primary energy source for the aquatic ecosystem. Hongve (1999) and Hongve et al. (2000) concur with this statement, also noting that humus-like substance and hydrophilic acids constituted the major fraction of dissolved carbon with large colour values.

2.6 Source and characteristics of major water constituents

The major constituents of natural water are dependent on the concentrations of their physical components (turbidity, conductivity, pH, temperature, colour, humus, total dissolved and suspended solids), nutrients (nitrogen and phosphorus), major cations (calcium, potassium, magnesium and sodium) major ions (chloride and sulphate) and metals (copper, iron and manganese). Each constituent can vary both spatially and temporally. By analysing these variables and comparing the values to developed water quality guidelines, an indication of the river catchment health can be determined. Table 2.1 summarises the general indicators used to assess catchment health and the potential impacts of excess amounts, while Appendix 1 contains concentration guidelines and natural sources of these parameters.

Table 2.1: General indicators of catchment health and the potential impacts of excessive amounts.

Indicator	Potential impact
Turbidity	Can cause changes in ecosystems, resulting in loss of sensitive species
Electrical conductivity	Salinisation, leading to the loss of sensitive species
pH	The internal pH of organisms is a critical factor in their existence, substantial variations can be fatal and lead to loss of sensitive species
Temperature	Important in the functioning of animals and plants
Colour	Influences rates of photosynthesis
Total nitrogen	Toxic effect on aquatic ecosystems including cyanobacterial blooms. Stimulation of plant growth and algae blooms
Total phosphorus	Excess amounts can trigger algae blooms which are a feature of eutrophication.
Chloride	Essential to plant growth, excess can cause leaf tip burning and yellowing
Calcium and magnesium	Together cause water hardness. Calcium is an essential element for all organisms, excess may cause calcarious formation in the body of animals.
Manganese	Can cause growth of slimes
Metals	High concentrations can have severe toxicological effects on the aquatic ecosystem

Source: Adapted from ANZECC (1996), NHMRC (2000) and Chapman (1990)

2.6.1 Physical components

2.6.1.1 Temperature

Water bodies undergo temperature variations along with normal climatic fluctuations. These variations occur seasonally and in some situations over a 24 hour daily period. The temperature of surface waters is influenced by latitude, altitude, season, time of day, air circulation, cloud cover, vegetation cover and the flow and depth of the water body (Chapman 1996; Fuller 1993).

Temperature has a substantial effect on the functioning of aquatic ecosystems with variations from the normal range leaving organisms exposed in a variety of ways. Growth and metabolism, timing and success of reproduction, mobility and migration

patterns may be all be effected to some extent (Fuller 1993). As water temperature increases, the rate of chemical reactions generally increases together with evaporation. Under such conditions, growth rates of bacteria and phytoplankton can also increase leading to enhanced water turbidity levels (Chapman 1996).

2.6.1.2 Hydrogen ion (pH)

The pH scale literally reflects the amount of hydrogen ions available in solution. The values of pH range between: 0 (highly acidic) 7 (neutral) and 14 (highly alkaline) (Fuller 1993). At any given temperature pH indicates the intensity of the acid or basic character of a solution and is controlled by the dissolved chemical compounds and biochemical process in the solution. In natural unpolluted waters pH, is principally controlled by the balance between the carbon dioxide, carbonate and biocarbonate ions as well as other natural compounds such as humic and fulvic acids (Chapman 1996).

While atmosphere and geology are the major features determining water pH levels, vegetation leachate also reduces pH through release of humic acids (Gallagher 1996). The internal pH of organisms is a critical factor in their existence and substantial variations can be fatal.

The pH of Tasmanian streams are generally in the range of 5.5 to 7.5, although streams on the west coast are often below 5.5, probably as a result of the high humic content from buttongrass leachate (Fuller 1993). Swaine et al. (1993) noted a marked reduction in pH and an increase in conductivity for selected southern Tasmanian unlogged small streams resulting from extreme flow changes over the seasons. pH varied from 8.2 in summer to 4.5 in the first month after winter. This seasonal change in pH was attributed to a relationship between water chemistry and soil processes.

2.6.1.3 Electrical conductivity

Electrical conductivity is the measure of the ability of water to conduct an electric current and is sensitive to variations in dissolved solids, mostly mineral salts. The degree to which these dissociate into ions, the amount of electrical charge on each ion, ion mobility and the temperature of the solution all have an influence on conductivity (Chapman 1996). Conductivity is expressed as microsiemens per

centimetre ($\mu S\ cm^{-1}$), and for any given water body is related to the concentrations of total dissolved solids and major ions.

During long, rain-free periods the supply of dissolved salts, relative to that of surface waters, will increase. This is especially so in catchments composed of calcareous rocks. During periods of high rainfall, and hence high flows, dilution of the groundwater flow by surface runoff will result. A negative correlation between flow and conductivity is therefore normally expected (King and Tyler 1978).

2.6.1.4 Turbidity

Turbidity is a measure of light scatter at 90 degrees to an incidental beam and tends to be caused by suspended materials such as colloids, particles, plankton or in turbulent waters, gas bubbles. High turbidity values indicate higher levels of suspended matter and reduced light penetration, while low values indicate clear water. High turbidity values cause a restriction on the availability of light to drive photosynthesis, thus reducing biological production and the amount of food availability to higher organisms. ANZECC (1996) recommends a guideline value change in seasonal nephelometric turbidity of no greater than ten per cent. Other guidelines (Liston and Maher 1997) recommend that to maintain moderate water quality, nephelometric units of 10, 15 and 20 should not be exceeded for eco-regions such as: mountains (> 500 metres), valleys (100- 500 metres) and plains (< 1000 metres), respectively.

2.6.1.5 Colour

Colour is caused by dissolved organic material and reduced light penetration by absorption. Two terms are used to describe colour. True colour is the colour after particulate matter has been removed. Apparent colour is the colour resulting from the combined effects of true colour and any particulate matter, or turbidity. Both are measured in Hazen units (CU). This study will only deal with apparent colour.

In natural waters, colour is due mainly to the presence of dissolved organic matter including humic and fulvic acids, which originate from soil and decaying vegetable matter (NHMRC 2000). Natural metallic irons (iron and manganese) can also contribute to natural water colour (Gallagher 1996).

Studies in the Yorkshire Dales (McDonald and Naden 1987) and the Derbyshire peak district (McDonald and Naden 1988) revealed that consistent differences occur between water colour in first order streams found adjacent to each other in apparently homogenous catchments. High water colour was attributed to catchments with organic rich soils on south facing slopes.

Mitchell and McDonald (1995) established that high water colour is a product of water table depression and elevated aerobic decomposition of upper organic layers, followed by catchment flushing. Soil organic content and soil moisture status was found to have major controls on the colour of water. It was also noted that colour is associated with other water quality variables. These observations suggest that high concentrations of metal irons as well as organic acid follow a similar process to that of water discolouration.

Analyses of water quality data produced a strong negative relationship ($P < 0.001$) between colour and pH, which was decided to be sufficiently strong to be used as a surrogate measure for colour. pH was found to drop rapidly just prior to a colour flush. A significant positive relationship also exists between colour and the concentration of iron ($P < 0.001$) and colour and the concentration of aluminium ($P < 0.001$). Colour and manganese concentrations are not correlated.

Strong positive relationships also occurred ($P < 0.001$) between pH and five metals tested, and between pH - conductivity ($P < 0.01$), pH - calcium and pH - magnesium, while pH - iron, pH - aluminium and pH-manganese are negative relationships. These results indicate that elevated discharge is characterised by water rich in organic products that increase acidity, discolour water and bring ions into solution. The findings also suggest that drying and wetting cycles in organic soils, responsible for water discolouration are also important in determining levels of other water quality variables.

Colour was also negatively correlated with slope in Mitchell and McDonald (1995) studies. Areas of slope $< 5°$ are plateau and have low conductivities, giving water the maximum potential to dissolve decomposition products and become coloured. When this is combined with drainage patterns water discolouration is promoted in two ways:

1. well-drained catchment will have a lower water table, producing a greater zone of aerobic decomposition and a large pool of organic, coloured water; and
2. high drainage density allows more rapid movement of drainage water, a faster export of solutes and therefore a more intense colour flush.

Buckney and Tyler (1973a) and Fuller (1993) found that in Tasmania, dark brown waters, thought to be derived from *Gymnoschoenus sphaerocephalus* (button grass), are characteristic of the south-west Tasmania region. Rivers in these areas tend to have twice the apparent colour than waters from the northern coast, east coast and Midlands area (Fuller 1993).

In Australia several studies (Oades 1982; Nelson et al. 1990) examined the origins and factors of influence of colour in water. Oades (1982) produced some predictions on where strongly coloured water might be found. These include; regions of intense organic matter oxidation, (i.e. wet tropic conditions and regions of high winter rainfall > 700 millimetres) and any water that is in prolonged contact with organic matter (e.g., peats, swamps, impounded water where organic matter, vegetation and soils are added) and after leaf fall in forests. A study by Nelson et al. (1990) agreed with these predictions of intense coloured water described by Oades (1982). This study compared two small catchments of different dissolved organic carbon concentrations. From this study it was concluded that waterlogging in winter where high amounts of soluble carbon exists, causes anaerobic conditions leading to denitrification and a darker water colour.

Several studies (Bowles et al. 1986; Gippel 1987; Hongve et al. 2000; Malcom 1985; Swain et al. 1993) discovered that vegetation and leaf litter, which decompose into the upper organic layers, are the major source of colour in streams. Gippel (1987) tested this conclusion through leachate experiments. Leaching of Eucalypt plant leaves produced the majority of colour concentrations in comparison to, plant wood, leaf litter, wet area litter and soils. Relative low amounts of colour could be extracted from soil material. On the basis of extinction coefficient and spectrum shape, stormflow colour most closely resembled the colour leached from upper soil layers and wet area litter deposits.

2.6.1.6 Humus

Stream humic substances are intimately related to all aspects of water quality. These substances which consist of complex metal ions (particularly iron), associated organic solutes and dissolved clay minerals, influence the cation – anion balance, thus imparting acidity and colouration to stream waters (Malcolm 1985). Humus is formed by the chemical and biochemical decomposition of vegetation residues and from the synthetic activity of micro-organisms (Gjessing 1975). Humus enters water bodies from the soil and from peat bogs, or can form directly within water bodies as a result of biochemical transformation.

Humus is separated into fulvic and humic acid fractions, each being an aggregate of many organic compounds of different masses. The yellowish-brown colour of the natural water is the water-extractable fraction of the soil humus and is called humic acid. Fulvic acid is similar but only found in the soil.

Gjessing (1975) states that iron is always found in coloured water, he demonstrated a positive correlation between dissolved organic carbon and iron in humus water, indicating that iron is bound to humus or parts of its organic matter. Low pH was only reported in waters high in humic acid.

Baker (1986) conducted experiments on humic substances and their role in the solubilization and transport of metals. It was found that 5 - 40 milligram per litre of humic substances was contained in several creeks in western Tasmania, while 430 milligrams per litre was found in a soil water sample. These experiments concluded that humic acids contribute about 85-98 per cent of the soluble organic substances present and are very mobile with rainfall.

In humid climates rainfall supplies water to a soil where bacterial action is continually producing humic substances. These substances along with numerous other biochemicals are located throughout the soil profile. Humic substances reach colloidal particle size and form complex formations between minerals, resulting in metals becoming highly mobile in the presence of water. In dry conditions the metal humates, together with the other metals absorb onto clay minerals, thus resulting in slow release of humic substances and iron oxides. However, when rainfall is

abundant the soil profile is subjected to the passage of soil water rich in solvents generated in the organic layer.

Day et al. (1991) studied two creeks in Victoria, (Australia), Slip and Myrtle, both with similar rainfall, geology and vegetation. Slip Creek was found to contain 20 per cent humic substances, whereas Myrtle Creek contains 52 per cent. Samples with higher natural organic matter had higher percentages of humic substances. The explanation for this difference in humic content is that the contact time between the water and the sediments, soil, vegetation and microbial community may control the concentration and nature of aquatic natural organic matter. Slip Creek is fed from a small spring at the headwaters and receives overland flow only during high rainfall. The residence time of waters in Slip Creek catchment is therefore limited, resulting in a short contact time with groundwater and associated sediments, soil, and vegetation, causing a low humic substance percentage. Myrtle Creek on the other hand is fed from groundwater and occasional overland flow, causing a longer contact time with water and a higher humic substance percentage.

2.6.1.7 Total dissolved and suspended solids

Total dissolved solids (TDS) consist of inorganic salts and small amounts of organic matter that are dissolved in water. TDS comprise sodium, potassium, calcium, chloride, magnesium, sulphate, bicarbonate, carbonate, silica, organic matter, fluoride, iron, manganese, nitrate, nitrite and phosphate (ANZECC 1996). TDS is often associated with inputs from rock weathering and the atmosphere. Total suspended solids (TSS) are composed of clay, silt, fine particulate and inorganic matter. TSS originates from the surface of the catchment and reflects turbidity in solution. High values of TSS typically form concentration peaks before storm peaks as a result of sediment exhaustion.

2.6.2 Nutrients

A wide range of nutrient concentrations has been reported for Australian rivers and streams with concentrations varying markedly with flow (Fuller 1993). Fuller's (1993) overview of water quality in Tasmania indicates that the state's waters are typically low in nutrients, unless pollution of the waterway has occurred.

2.6.2.1 Nitrogen compounds

Nitrogen is essential for living organisms and is an important constituent of proteins, including genetic material. Plants and micro-organisms convert inorganic nitrogen to organic forms. In the natural environment inorganic nitrogen occurs in a range of oxidation states including nitrate (NO_3^{2-}), nitrite (NO_2^-), ammonium (NH_4^-) and organic nitrogen (N) and together these are known as total nitrogen (TN) (Chapman 1996).

Ammonia occurs naturally in water bodies arising from the breakdown of nitrogenous organic and inorganic matter in soil and water, excretion by biota, reduction of the nitrogen gas in water by micro-organisms and from gas exchange with the atmosphere. Natural seasonal fluctuations occur as a result of death and decay of aquatic organisms (Chapman 1996). Total ammonia concentrations measured in surface waters are typically less than 0.2 milligrams per litre and higher concentrations can be an indication of organic pollution. With certain pH levels, high concentrations of ammonia are toxic to aquatic life and hence ammonia is a useful indicator of organic pollution.

The nitrate ion is a common form of combined nitrogen found in natural waters. Nitrate can be biochemically reduced to nitrite by denitrification processes, usually under anaerobic conditions. Natural sources of nitrate in surface waters include, igneous rocks, land drainage and plant and animal debris. It is an essential nutrient for aquatic plants with seasonal fluctuations usually caused by plant growth and decay cycles.

Nitrate leaching from natural vegetation is normally minimal and natural concentrations seldom exceeding 0.1 milligrams per litre. Nitrite concentrations in freshwaters are usually very low, < 0.001 milligrams per litre (Chapman 1996). Higher concentrations in rivers occur during baseflow periods, when groundwater discharge is highest (Chapman 1996). Determination of nitrate plus nitrite in surface waters gives an indication of the general nutrient status and levels of organic pollution.

2.6.2.2 Phosphorus compounds

Phosphorus is an essential nutrient for living organisms and exists in water bodies in both a dissolved and particulate form. Phosphorus is generally the limiting nutrient for algae growth and therefore controls the primary productivity of the water body. Natural sources of phosphorus are mainly derived from the weathering of phosphorus bearing rocks and the decomposition of organic matter (Chapman 1996).

Phosphorus is rarely found in high concentrations in freshwater as plants actively take it up. Concentrations in freshwater can range from 0.005 to 0.020 milligrams per litre, with concentrations as low as 0.001 milligrams per litre in pristine water (Chapman, 1996). Although plants generally require phosphorus in its dissolved form, it moves between various dissolved and particulate forms continuously depending on environmental conditions and processes. The measurement of total phosphorus is considered the best form to analysis as it includes both particulate and dissolved forms (Bobbi et al. 1999).

2.7 Summary

This chapter provided a literature review outlyining the reasons for natural water quality variations and discussed the source and characteristics of major water constituents. Understanding natural sources of various components found in streamwater is an important procedure, which is essential for comparisons between pristine and impacted catchments, and for the evaluation of disturbances within particular catchments. When examining small differences between catchments where disturbances could impact on the water quality it is extremely important to have an understanding of the natural processes (chemical rock weathering, atmospheric inputs, decaying vegetation and the leaching of organic soils) that affect the water in that particular area. Other factors of importance include water volume, the flowpath of the water moving through the catchment and its residence time within particular parts of the catchment. Any of the natural processes discussed can have a significant impact on the water quality of a particular stream and must be taken into account when relating water quality data to national concentration guidelines.

Chapter 3: Dynamics of Tasmanian waterways

3.1 Introduction

The current knowledge on water quality in Tasmania with particular emphasis on the south-western portion of the state are reviewed in this chapter. Variations in water compositions and the reasons for these differences are discussed.

The island of Tasmania is situated on the southeastern edge of the Australian continental plate. It is characterised by low levels of atmospheric pollution, which is attributable to prevailing south-westerly winds from the Southern Ocean, low human population density, and the absence of large-scale industrial activity (Cameron et al. 1993). The mountainous regions of Tasmania's Wilderness World Heritage Area and its district of lakes and rivers are of immense beauty and interest with great limnological and biological diversity (Tyler 1992). Tyler (1974) divided Tasmania into western and eastern provinces based on changes in climate, relief, geology, soils and vegetation. Differences in water composition between east and west Tasmania are discussed along with detailed studies of particular areas.

3.2 Composition of Tasmanian waters

Williams (1964) first surveyed the water quality of Tasmania's lakes (Buckney and Tyler 1973) and demonstrated that the geology and climate of the area largely affect the chemical constituents of Tasmanian freshwater. Williams (1964) noted that Tasmania is a geologically ancient island with Cambrian and Precambrian rocks on the western side, while the centre and large areas on the East Coast consist of mainly Jurassic dolerite. A large proportion of the state is also above 500 metres and as such is greatly affected by the topography producing considerable local climatic variation.

Buckney (1971) stated that the knowledge of Tasmanian waters was very limited and aimed to extend the assessment of Tasmania's water by surveying a large number of lakes and rivers. As a result of this study, Buckney (1971) divided Tasmania into seven distinct regions, based on the chemical constituents of the water found within

these areas. The southwest region, which contains the Warra LTER area, contains two types of water quality, which are of limited occurrence elsewhere in Tasmania.

Type one water is characteristically highly coloured and occurs in areas where peats overlie inert rocks such as quartzites. The dominant vegetation is buttongrass (*Gymnoshenus sphaerocephalus),* which establishes in areas of poor drainage or frequent fire frequency. Peat was thought to contribute to the production of coloured waters. Type one waters exhibit ionic proportions close to seawater and have a dominance order of: $Na^+ > Mg^{2+} > Ca^{2+} > K^+ - Cl^- > SO_4^{2-} > HCO_3^-$ with a pH < 5.5.

Type two water drains the easily weathered calcareous and igneous rocks such as limestones, serpentines and dolomites. Calcium and magnesium from these rocks enter solution as the bicarbonates. Dominance orders consist of: $Ca^{2+} > Mg^{2+} > Na^+ > K^+ - HCO_3^- > Cl > SO_4^{2}$ with a pH > 7.5.

In the Central Plateau region (another distinct area of land studied by Buckney (1971)), type three water drains dolerite catchments and vary in composition from a colourless, less-acidic type one water to something approaching type two water. The range of chemical dominance reflects a number of influences including the weathering state of the rock, magnetic differentiation of the rock, interaction of atmospheric supply of salts, geological influence and vegetation effects (Buckney 1971).

After examining numerous water bodies in Tasmania, Buckney (1971) developed some statements about water bodies on the island:

1. all coloured waters are acidic;
2. iron concentrations are always low except in the coloured waters, where concentrations of 0.5 parts per million may be found;
3. the coloured waters have ionic proportions closest to seawater;
4. most uncoloured waters are found in dolerite catchments, where calcium is in greater proportion than 50 per cent of total cation concentrations; and
5. bogs, peats and similar vegetation types all appear to be characterised by their association with coloured waters and atmospheric supply of salts appears to be the main determinant of water characteristics on inert rocks.

Buckney and Tyler (1973b) further studied the proposal of different geology and climatic patterns influencing water composition. Tasmania lies within latitudes affected by the westerly airstream of the "Roaring Forties". This combined with the disposition of mountain ranges, accounts for a west-east rainfall gradient. The climatic and geological discontinuity is reflected in pronounced vegetation differences. Temperate rainforest, rainforest or sedgeland dominates the wet areas while dry sclerophyll or epacrid heath covers the drier east (Buckney and Tyler 1973b). This division became known as Tyler's line, and runs roughly north-west by south-east angled across the 146th meridian

The western province is described by Tyler (1974) as a jagged landscape of ancient rocks mantled by peat-forming rainforest and sedgeland, where creeks run, enriched with minerals, to brown water lakes. The eastern province is a younger, flatter landscape, covered by sclerophyll forest of *Eucalyptus*, with crystal clear, deep green lakes and no peat extracts. Minerals from the soluble rocks give the lakes distinctive chemistry that approaches chemical concentrations of world fresh water (Tyler 1992). Warra LTER site sits between the east and west ecological divide and contains a mixture of both terrestrial conditions (Table 3.1)

Table 3.1: East and west ecological divide and its terrestrial divisions.

East Tasmania	West Tasmania
Jurassic-Tertiary dolerite basalt sediments	Permian, Carboniferous sediments
Miscellaneous soils	Mix of podzols and moor peats
Sclerophyll forests	Rainforest, alpine mosaics
Deep green water lakes	Brown water lakes

Source: (Tyler 1974)

Buckney and Tyler (1973a) refined the original division of seven provinces made by Buckney (1971), down to five water chemistry provinces that reflect the above prevailing environmental conditions. These provinces are the south-west and west; the central plateau; the north-west; the midlands, east and north and the Bass Strait islands. The two provinces, which are of importance when categorising waters in the Warra region, are; the south-west and west and the central plateau.

The south-west waters vary in composition depending on the nature and degree of geological influences. At one end of the spectrum are brown, acid waters, with ionic proportions very close to seawater and at the other end are waters showing marked geochemical influences of weatherable rocks not covered by deep peats. The Warra region sits in this end of the spectrum.

There were, however, several locations that did not fit within the above ionic dominance. These samples are of particular importance because they include the Weld and Huon rivers, which border the Warra region. These samples when plotted against other samples from the region are distinct outliers and show ionic proportions halfway between 100 per cent calcium and 100 per cent magnesium and very close to 100 per cent HCO_3^- (Buckney and Tyler 1973a).

The central plateau is an area of Dolerite > 600m in altitude. Lakes in areas of high rainfall contain ionic dominance waters similar to seawater. However, the remaining lakes display ionic proportions of Ca^{2+} and HCO_3^- dominance. Most of these waters are colourless, but in the west local sedgelands may contribute allochthonous humic material (Buckney and Tyler 1973a)

The waters of Tasmania have therefore been categorised into distinct regions based on their geology, climate, soils and vegetation. This grouping that is based mainly on water chemical properties in lakes does not however hold true when small catchments and in particular rivers are examined. Tyler (1992) described the problems associated with categorising Tasmanian water bodies, based on their catchment characteristics and demonstrated that the precise chemical characteristics that determine the chemical and optical differences are not fully understood.

Tyler (1992) used Lake Judd as an example where ionic proportions do not reflect the climate, vegetation and geology that surrounds them. Lake Judd lies in a glacial chasm carved in a tongue of dolerite bulging into the western rock province. To the north, south and west are typically dark, western lakes. Its small limited catchment is densely clothed in temperate rainforest and it would seem to have all the necessary ingredients for a dystrophic lake. However, the lake only contains very light brown water.

The areas where chemical constituents vary from the ionic proportions around them are due to particular catchment characteristics. These characteristics are particularly important in rivers where waters pass through a variety of rock and vegetation types within a catchment. Since the late 1970s in Tasmania, particular river catchments and lake districts have been examined to determine their ionic compositions and the source of any discrepancies from the surrounding provenance.

Vyverman et al. (1996) studied the general characteristics of lakes in Tasmania to better understand the distribution of benthic assemblages. The results concur with those discussed by Tyler (1992). Essentially the outcomes indicate the existence of major gradients from western lakes (composition close to seawater) to eastern lakes (composition closer to world average freshwater). These gradients were again partially explained by the similar gradient in mean annual rainfall and geological differences. Vyverman et al. (1996) established that geological content and rainfall regime are likely to influence lake-water chemistry

3.3 Gordon River Basin

King and Tyler (1978) studied the waters of the Gordon River Basin and discovered geochemical influences with a resulting modification of the water. The limestone sequences of the Gordon River Basin produce waters with abnormally high proportions of sodium and calcium, a fact attributed to the marine origin of the limestone. When flows are quite low the Gordon River water originates largely from ground water storage, which is alkaline. However, when flows are high during winter, sodium and chloride dominates. The river water is then similar in ratio to seawater. This pattern occurs in rivers from catchments with abundant calcareous rocks, but elsewhere the chemical composition was similar to seawater (calcium and magnesium should be approximately equal) irrespective of flow.

King and Tyler (1978) also assessed several rivers and creeks in the Franklin River catchment headwaters and found a good correlation between variations in flow and a number of chemical parameters. When flows were high they were accompanied by high colour. However, Watson (1978) found that in low flows, the Gordon River limestone basin displays geochemical influence and modification of the water, with

chloride contributing about 40 per cent of the total anions and principle cations occurring in equal proportions.

This difference in chemical parameters such as pH, calcium, alkalinity, dissolved organic carbon and conductivity is due to the widespread presence of limestone in the Gordon River tributary catchment, compounded by significant dilution of these parameters by rainfall (Koehnken 2001). Koehnken (2001) established that sodium and chloride values are highest in tributaries located closest to the coast, reflecting marine aerosols derived from westerly airstream.

Buckney and Tyler (1973b) described the major chemical features of the surface waters of Lake Pedder as being low in ionic strength with a high humic content and a chemical composition similar to that of seawater. The lake receives its water from the Serpentine River that drains sedgelands, dominated by *Gymnoschoenus spaerocephalus*. The waters of Lake Pedder are therefore similar to the surrounding acidic brown waters of Western Tasmania. However, the decomposition of sedgeland peats contributes considerable organic matter, accounting for high acidity, colour, and low bicarbonate content (Buckney and Tyler 1973).

3.4 Warra LTER and the surrounding area

The geology of the Hartz region was studied by Knott et al. (1978) and found to be similar to that of many other peaks in the fault structure province (Jurassic dolerite, overlying Triassic sandstone). The lakes in this area were discovered to be weakly acidic, with dilute ionic waters. All samples showed a seawater dominance and in this respect did not differ from other dolerite waters in Tasmania. However, increased proportions of some major ions, particularly sodium was present in several samples (Knott et al. 1978). This type of enrichment has been detected in 20 per cent of Tasmanian water samples analysed by Tyler (1974). Such deviations in anionic or cationic proportions are usually considered to be due to geochemical influences (Buckley and Tyler 1973a), but Knott et al. (1978) found no reason to suggest that the dolerite of Hartz Mountain is unusual in its composition or weathering.

On the Picton Massif there are a number of lakes and tarns, Tyler (1993) found that in their water chemistry they resembled lakes found on the Central Plateau and elsewhere in Tasmania where dolerite occurs. These water bodies contain an ionic composition between seawater and world average freshwater (Tyler 1993).

Maintenance of seawater ionic proportions requires that the waters are isolated from geochemical influence, or come into contact with only inert rocks. Both conditions are met in the south-west where peat derived from button grass overlies inert Precambrian rocks. The humic waters draining the Huon Plains have a high Oceanic Origin Factor (OOF). Hanging Lake on Federation Peak, a Precambrian range, has an OOF of 94.5 per cent. Lake Picton on Jurassic dolerite has an OOF of 80.1 per cent. However, the Weld River draining from the flanks of Mount Anne has an OOF of only 12.2 per cent with dominance order of $Mg^{2+} > Ca^{2+} > K^{+} > Na^{+}$ - $HCO_3^{-} > Cl^{-} > SO_4^{2-}$ and is therefore a rock dominated catchment (Tyler 1974).

In the Warra LTER site (lying between the Huon and Weld Rivers), water samples from 16 streams have been collected in a fortnightly monitoring program since 1999 (Ringrose and Meyer 2001). These samples cover a range of flow rates from base level to storm events and a range of conditions and stream characteristics. Water in these streams was coloured by naturally leaching organic compounds. Within the Warra area, 14 of the sampled sites are coloured to some extent and two, Crystal and Isabella Creeks, are clear (Ringrose and Meyer 2001). Ringrose et al. (2001) demonstrated that water quality significantly changes during storm events in creeks within the Warra LTER site. As flow increases, turbidity levels increase rapidly with the start of increased flow and then tail off. The turbidity profile changes with the season and catchment hydroclimatic conditions.

3.5 River Derwent Catchment

Buckney (1977) examined chemical changes in the River Derwent during 1972-73, and discussed the broad chemical variability found. Water samples were collected monthly from the Plenty River, which is at the base of the catchment.

The majority of the River Derwent catchment consists of Jurassic dolerite, with some Tertiary rocks at the lower altitudes. Colour was highest during the flood periods, lowest during the ends of the winter months and tended to rise during the summer period. High pH values were maintained during the summer, with lower values occurring during the winter which has been described as a response to changes in photosynthetic activity in rivers. The most marked chemical changes were associated with high flows where colour, turbidity and sodium and chloride concentrations increased. This is seen as characteristic of the early stages of floods and produced significant correlation at the 95 per cent confidence level.

Buckney (1977) concluded that as long as the river was not in flood conditions, the broad chemical behaviour for the River Derwent during increased discharge was as follows:

1. the concentrations of sodium, potassium, chloride and silica fell;
2. the concentrations of calcium, magnesium, bicarbonate and sulphate fell; and
3. the total chemical concentrations and pH fell.

3.6 Summary

The surface waters of Tasmania are categorised into regions, based on the influence of geology, climate, soils and vegetation. These effects result in changes to the physical and chemical constituents found in Tasmanian freshwater. Two distinct types of water occur, uncoloured waters with ionic proportions approaching world freshwater concentrations (affected by geochemical influence) and coloured waters with ionic proportions close to seawater concentrations (isolated from geochemical influence). However, in uncoloured waters during periods of high flow, high levels of colour, turbidity, sodium and calcium are flushed from the catchment.

An east west divide known as Tyler's line separates these two types of water. The Warra LTER sits within this line and therefore contains both coloured and uncoloured waters. Analysis of Warra (coloured) and Crystal (uncoloured) Creeks will therefore expand the current knowledge of water quality in these intermediate areas.

Tasmanian waterways have been studied to a moderate degree, with the majority of work conducted on water from lakes. Very little work has been conducted on the water quality of small forested catchments in Tasmania and the source of unexpected elevated chemical constituents within rivers. The reasons behind differences in water quality in Tasmanian surface waters were reviewed in this chapter.

Chapter 4: Methodology

4.1 Introduction

Since 1999 Forestry Tasmania has regularly monitored Warra and Crystal Creeks through a fortnightly snapshot sampling regime (Meyer et al. 2002a; Meyer et al. 2002b). Warra Creek also has a weir built upon it, where continuous monitoring of temperature, turbidity, conductivity and flow has been in place since May 1999 (Ringrose and Meyer 2001; Ringrose et al. 2001).

Results from Forestry Tasmania indicate that several pristine streams carry water coloured with organic matter. A significant variation of water quality has also been found between streams, independent of logging regimes. For example, Warra Creek has a low base flow turbidity of < 1 NTU, but an average turbidity of 11.5 NTU (Ringrose et al. 2001).

This chapter discusses the design of the study used to achieve the stated aims and objectives, the parameters selected for the assessment of water quality, field instrumentation used to collect the water samples, assessment of soil types and data analysis utilised for the interpretation of the results.

4.2 Experimental design

The experimental aim and objective of this study are to determine the apparent source of colour and nutrient enrichment in the pristine stream of Warra Creek catchment and investigate the differences in water quality between Warra and Crystal Creeks. Composition of water to a large extent depends on its pathway through the catchment and is dependent on the percentage of groundwater, subsurface and surface flow present in the creek. The experimental design was therefore intended to encompass the range of catchment flow conditions found within the two creeks. Water samples were taken during fortnightly visits and during two storm events. Warra Creek catchment was further examined by collecting "snapshot" water samples through different flow conditions at several locations along its watercourse,

with the aim of determining the source or sources of nutrient enrichment. To assist in the interpretation of the water quality data, soil, vegetation, geology, fire history, and slope patterns were examined and mapped for both Warra and Crystal Creek catchments.

Fortnightly sampling was undertaken at the base of the catchments of Warra and Crystal Creeks where measurments of turbidity, conductivity, pH and temperature were undertaken. Temperature was recorded in the field, while conductivity, pH and turbidity were recorded the following day at Forestry Tasmania's laboratory.

Two storm events at both Warra and Crystal Creek were sampled, one in autumn and the other winter. Water was collected over a 48-hour period and all samples were analysed for turbidity, conductivity and pH. From these samples, ten were selected for analysis of the full range of parameters (Table 4.1). The samples were collected from just prior to the storm event, through to the peak of the flow height and up to 24 hours after the event.

A snapshot sampling regime was conducted at five locations up Warra Creek and at the base of Crystal Creek. Sampling occurred during summer, winter and spring baseflow levels and in a winter highflow level (storm), all parameters were analysed. The sampling locations were designed to collect water from above and below small tributaries leading into Warra Creek, Figure 5.3 displays the location of these sampling points.

4.3 Water quality parameter selection

A variety of parameters, used as both general and point source indicators were selected for analysis. These parameters were selected to identify inputs into the river systems and their potential sources. They do not necessarily indicate artificial pollution sources or logging impacts, but are aimed at collecting the majority of important constituents resulting from the atmosphere, vegetation and associated biological processes, geology and associated soils.

Table 4.1: Parameters used for the assessment of water quality in Warra and Crystal creeks.

Physical indicators	**Major ions: anions**
Temperature - measured in degrees Celsius	Chloride - measured in mg/L
Turbidity - measured in NTU	Sulphate - measured in mg/L
Electrical conductivity - measured in $\mu S/cm^{-1}$	
pH - measured as -log[H^+]	**Major ions: cations**
Apparent colour - measured in Hazen units	Total calcium - measured in mg/L
Total dissolved solids – measured in mg/L	Total potassium – measured in mg/L
Total suspended solids – measured in mg/L	Total magnesium - measured in mg/L
Nutrients	Total sodium - measured in mg/L
Ammonium ion - measured in µg/L	
Nitrate and nitrite - measured in µg/L	**Metals**
Nitrite - measured in µg/L	Total copper - measured in µg/L
Total nitrogen - measured in µg/L	Total iron - measured in µg/L
Ortho – phosphate - measured in µg/L	Total manganese - measured in µg/L
Total phosphorus - measured in µg/L	

4.4 Field instrumentation and method analysis

Water samples were collected in polyethylene bottles for the analysis of conductivity, pH, and turbidity, and assessed in Forestry Tasmania's laboratory by a variety of meters. Conductivity was measured with a temperature compensated microprocessor conductivity meter model LF 196, pH was measured with a microprocessor pocket ph/mv meter and turbidity was measured with an Analite portable nephelometer, model 156. Samples were stored at 4°C until the analysis was completed, which was always within two days of sampling. The Analytical Services Tasmania - Department of Primary Industries, Water and Environment (DPIWE), a NATA (National Association of Testing Authorities, Australia) accredited laboratory, checked a subset of results (no discrepancies were found).

Other samples were collected in sterilised polyethylene bottles that were rinsed twice with the stream water before capping commenced. These samples were then delivered to the Analytical Services Tasmania laboratory, either on the day of sampling or the following day. All samples were analysed for their individual parameters by methods based on *Standard Methods for the examination of Water and*

Wastewater (20th edition) and are covered by the laboratory NATA registration. Nutrients were analysed colorimetrically using a Skaler Autoanalyser, anion analysis was by Liquid Chromatography using a Dionex DX 100 Ion chromatograph while cation and metal samples were analysed by a Varian Vista Inductive Coupled Plasma – Atomic Emission Spectrophotometer.

Storm samples were collected by two Trade 12M Gamet automatic liquid sampling systems. The Gamet water sampler is a self-contained transportable battery operated machine that pumps and collects water samples from a source at regular time intervals. Both Gamets were set up on a float-activated system, designed to begin sample collection once the water level reached a predetermined height. In the autumn storm, samples were collected every two hours, for 48 hours. However, due to quicker changes in flow height, samples were collected every hour during the winter storm. All samples were then analysed for turbidity, conductivity and pH at Forestry Tasmania's laboratory. Based on the initial results and the hydrograph of the storm, ten samples were sent for full parameter analysis at the Analytical Services Tasmania Laboratory.

Stream flow of Warra Creek was measured continuously at a weir. A continuous record of the height in the pond is obtained from a float-activated Unidata Shaft Water Level instrument. A Unidata Starlog Datalogger encoder recorded information on fifteen-minute intervals. The stream flow of Crystal Creek was recorded from an in-stream stage height board located at the sampling point. Stream heights were recorded whenever samples were collected. Further information on the weir design is described in Ringrose and Meyer (2001).

Rainfall data from the Bureau the Meteorology's Grove Research Weather station are presented in Chapter seven. Data from this station were presented in the same format as that used in water flow heights for Warra Creek. Thus allowing a direct comparison between effects of rainfall on stream height and the resulting water quality .

4.5 Soil transects and analysis

Soil and site surveys were carried out along the two access tracks within Warra Creek Catchment (Figure 6.1). Intensive sampling was carried out on either side of the creek bed and at several other locations within the catchment. A total of twelve sites were examined by either a hand auger or through the digging of soil pits. The soils from each sampling location were classified according to MUNSELL (2000) soil colour charts and the Australian soil and land survey field handbook (McDonald et al. 1990). Site surveys including recording the Global Positing System of each survey point, classification of the geological parent material and a vegetation description based on species present concluded the survey.

After taking into account previous soil descriptions of the Warra area (Laffan 2002), vegetation mapping sheets (Corbett 1997), geology mapping sheets (Mineral Resources Tasmania 1997) and other related texts on the subject (Davies 1988; Pemberton 1989; Tarvydas 1978) a map of the soil types of the Warra catchment was produced (Figures 6.2 and 6.3).

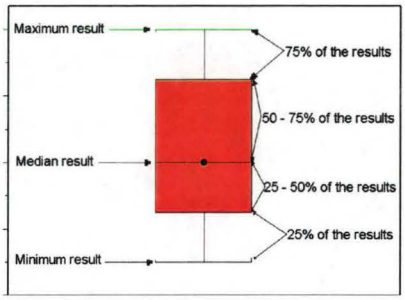
4.6 Data analysis and interpretation

Results were presented in a variety of ways depending on the type of data collection. Fortnightly samples were displayed in bar graphs of raw data, with box and whisker plots used to interpret the distribution of individual parameters and Pearson product correlations performed between all pairs of parameters. In the snapshot sampling program each parameter was analysed for total concentrations at each sampling location (box and whisker plots) and total concentrations per hectare of contributing land above each sampling location (bar graphs). Storm samples are shown in line graphs of raw data with correlations performed between all pairs of parameters. All results are presented in full in the Appendices.

Raw data are displayed in either bar or line graphs, depending on the amount of samples collected. These types of graphs best display the trends of individual parameters through the seasons and across the year.

Box and whisker plots were produced with S-Plus 6 Professional for Network Servers statistical software package. These plots are used to illustrate the distribution and summary statistics of individual parameters. The whiskers on the graph are the maximum and minimum recorded values, with the box representing the middle per cent of the values (Figure 4.1). The middle of the box is the median (centre of distribution). Averages are generally not used for water quality parameters because the data are not normally distributed (Chapman 1996).

Figure 4.1: Interpretation of a box and whisker plot.



Pearson product correlations between each pair of parameters were produced from the raw data with the use of StatGraphics software package. These correlation coefficients reported as r^2 values range between +1 and –1 and measure the strength of the linear relationship between the parameters. The statistical significance of these estimated correlations is then tested by probability values. Probability values below 0.05 indicate statistically significant non-zero correlations at the 95 per cent confidence level. Correlation coefficients can be significant without being strong, with small r^2 values showing significance in large enough sample sizes. r^2 values were labelled depending on their correlation coefficient number in the following manner:

0 – 0.2 = Very weak correlation;
0.2 – 0.4 = Low correlation;
0.4 – 0.6 = Moderate correlation;
0.6 – 0.8 = Strong correlation; and
0.8 – 1.0 = Very strong or a perfect correlation.

4.7 Summary

The methods used to conduct the water quality investigation into Warra Creek catchment have been presented in this chapter. The research was designed to gain an understanding of differences between Warra and Crystal Creeks and thus the effects of different catchment types on water quality. Further analysis of vegetation, geology, atmospheric inputs, soil and litter leachate interactions are required to gain a more thorough understanding of the natural changes that impact on water quality. The location of the study sites, and discussion of geology, vegetation, soils, topography and fire history found in each catchment are detailed in chapter five.

Chapter 5: The catchments

5.1 Introduction

Maps and descriptions of study sites, geology, vegetation and fire history of the two catchments along with reviews of soil and topography information are detailed in this chapter. The study sites are located within the Warra LTER area, between the boundaries of the Huon and Weld River, in the Picton Valley in southern Tasmania (146° 40' east, 43° 04' south). Warra lies approximately 60 kilometres south-east of Hobart and is reached by travelling on the Arve Road, accessed at Geeveston (Figure 5.1). The area is 15 900 hectares and has a range in altitude of 37 – 1260 meters.

Figure 5.1: Location of Warra LTER site.

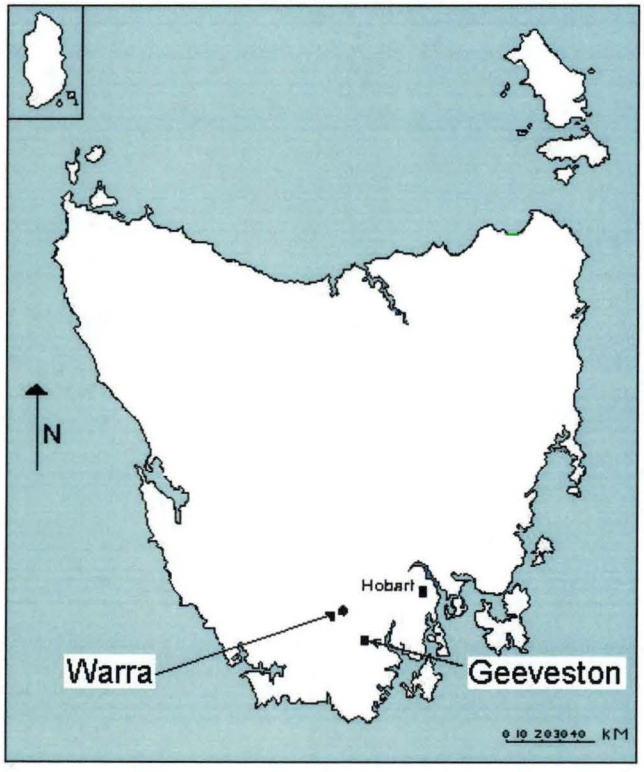
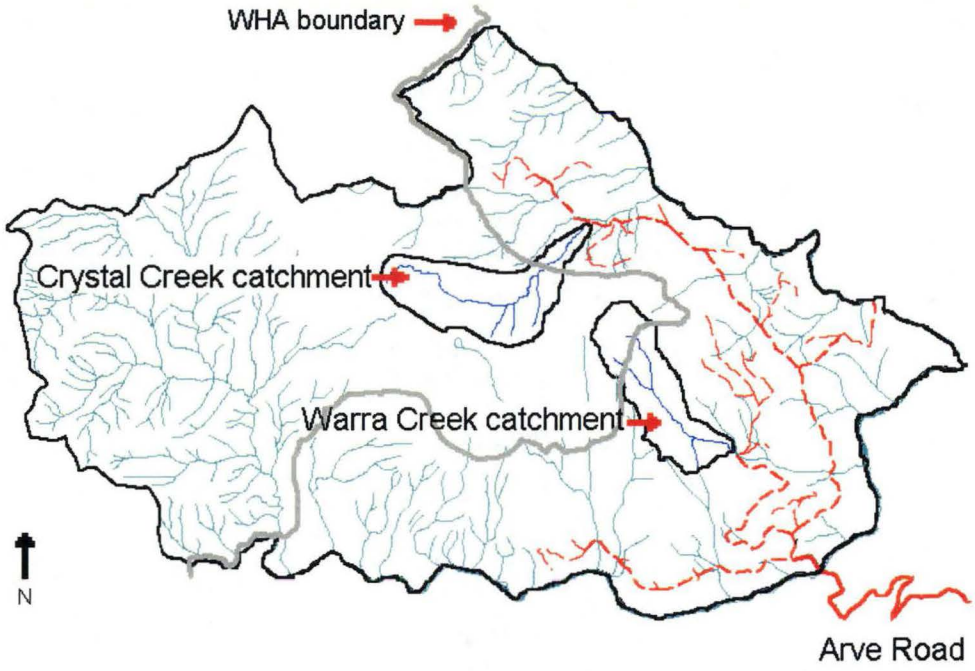


Figure 5.2: Warra LTER site showing Tasmanian Wilderness World Heritage area boundary and catchment locations.



5.2 Study sites

The study sites, known as Warra and Crystal Creek are located in the Warra LTER area. Warra Creek catchment drains from the southern side of Mount Frederick, while Crystal Creek catchment drains from the eastern side of the mountain. The Warra catchment consists of 412 hectares of undisturbed forest. Five study locations occur along this creek (Figure 5.3). The study sites are spread along the course of the creek, from the top of the catchment to the Warra weir site, (located above Warra road).

The Crystal Creek catchment consists of, 550 hectares of pristine forest, with 30 hectares of forest regeneration (1993) on the bottom part of the catchment. One study site is located within this catchment (Figure 5.4). Altitude and specific locations of all study sites are presented in Table 1. The study sites altitude, specific location and contributing catchment areas are discussed in Table 5.1.

Table 5.1: Study site details.

Site	Easting	Northing	Altitude (metres)	Contributing catchment area (hectares)
Warra #1	0474198	5232534	560	124.9
Warra #2	0474013	5232406	567	52.7
Warra #3	0474697	5231646	480	282.4
Warra #4	0475201	5231223	450	311.5
Warra Weir	0475883	5230989	350	412
Crystal Creek	0472738	5235980	300	550

Figure 5.3: Warra Creek catchment displaying study site locations and contours.

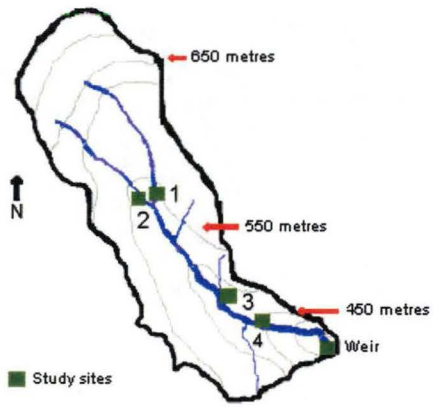
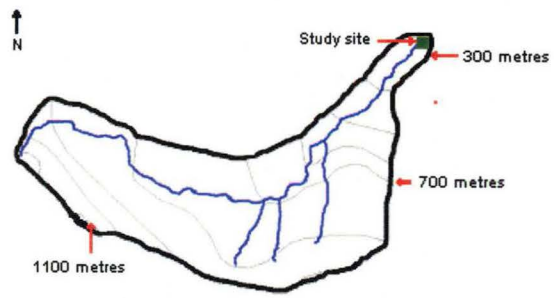


Figure 5.4: Crystal Creek catchment displaying study location and contours.



5.3 Geology

Jurassic dolerite and derived Quaternary slope deposits dominate the geology of Warra LTER site. The Warra catchment as shown by the 1995 Mineral Resources survey map is composed largely of Jurassic dolerite. However, recent access roads in areas southeast of Mt Fredrick at about 600 metres (near water sampling sites 1 and 2) have led to the discovery of Permian sedimentary rocks including massive

sandstone layers interbedded with fossiliferous siltstone (Corbett 1997) (Figure 5.5). Crystal catchment is composed of Quaternary talus consisting predominantly of Jurassic dolerite boulders, with some Jurassic dolerite in the headwaters of the catchment. The lower reaches of the catchment immediately around the river course contains Permian sedimentary sequences, consisting largely of marine mudstone and siltstone (Figure 5.6).

Laffan (2002) describes the Jurassic dolerite (c. 170 million years) from the Warra LTER site as being typically very hard, dark bluish-grey crystalline rock, varying in grain size from very fine to medium. It weathers to form a distinctive yellow-brown or orange-coloured rind around exposed basement rocks and floaters. Quaternary deposits in the Warra site (c. < 1.8 million years), include alluvial deposits, exposed colluvium on hill slopes, and minor morainal deposits (tills) at higher elevations (Laffan 2002).

Figure 5.5: Geology of Warra Creek catchment (modified from the 1995 Mineral Resources survey map).

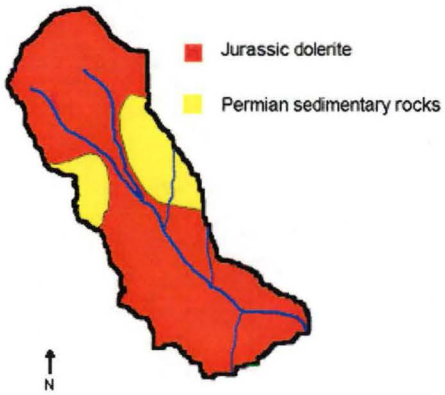
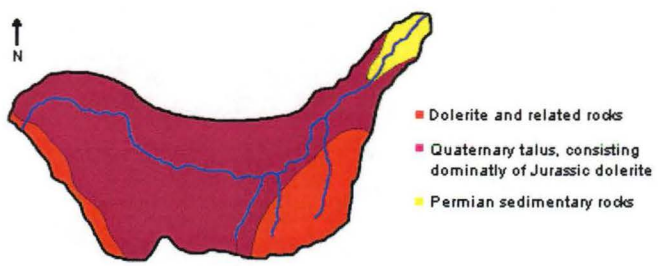


Figure 5.6: Geology of Crystal Creek catchment (modified from the 1995 Mineral Resources survey map).



5.4 Vegetation

Corbett (1997) has described the vegetation of the Warra LTER site and produced a vegetation map of the major changes at 1:25000, based on aerial photography and field verification. This vegetation mapping project found that the physical and chemical properties of the substrate have a marked effect on the type of vegetation present.

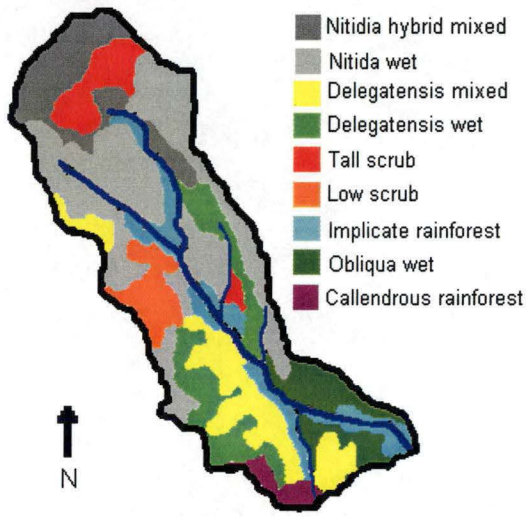
Jurassic dolerite weathers to produce a red soil with fairly high fertility (Corbett 1997). These fertile red soils give rise to rainforest, mixed forest, wet sclerophyll and dry sclerophyll at lower altitudes and some subalpine rainforest shrubberies. Wet heaths with an open canopy of *Eucalyptus coccifera*, *Melaleuca* moorlands are formed at intermediate altitudes and alpine rainforest shrubberies, alpine heaths and sedgelands at high altitudes.

Other important bedrock types found in the two catchments are the Permian sedimentary rocks that have in some cases exerted strong influence on the vegetation. These sandstone rocks (as seen near sites 1 and 2 in the Warra Creek catchment) have weathered to produce extensive infertile soils which carry *Eucalyptus nitidia* and tea tree scrub rather than the *E. delegatensis* wet forest characteristic of the intervening dolerite strips. This vegetation is interpreted as being the same as that typically found in south-west Tasmania on siliceous substrates (Corbett 1997). However, below 500 metres altitude Permo-Triassic sedimentary rocks weather to produce soils of moderate fertility. These soils produce canopy vegetation similar to thc surrounding dolerite (as seen in the lower part of Crystal Creek catchment), but with an understorey dominated by *Leptospermum scoparium* and sometimes *Banksia marginata*.

At low altitudes, forests contain *E. obliqua* and *E. regnans*, between 400-500 metres there is a transition zone where *E. obliqua* and *E. delegatensis* both occur, with a few *E. johnsoni*. Above 500 metres *E. delegatensis* is dominant, with significant numbers of *E. subcrenulata* and a tall white gum which may be a hybrid between *E. nitida* and *E. coccifera*. Above 600-700 metres both of these species give way to *E. coccifera*, which extend till about 900 metres, where *E. vernicosa* appears.

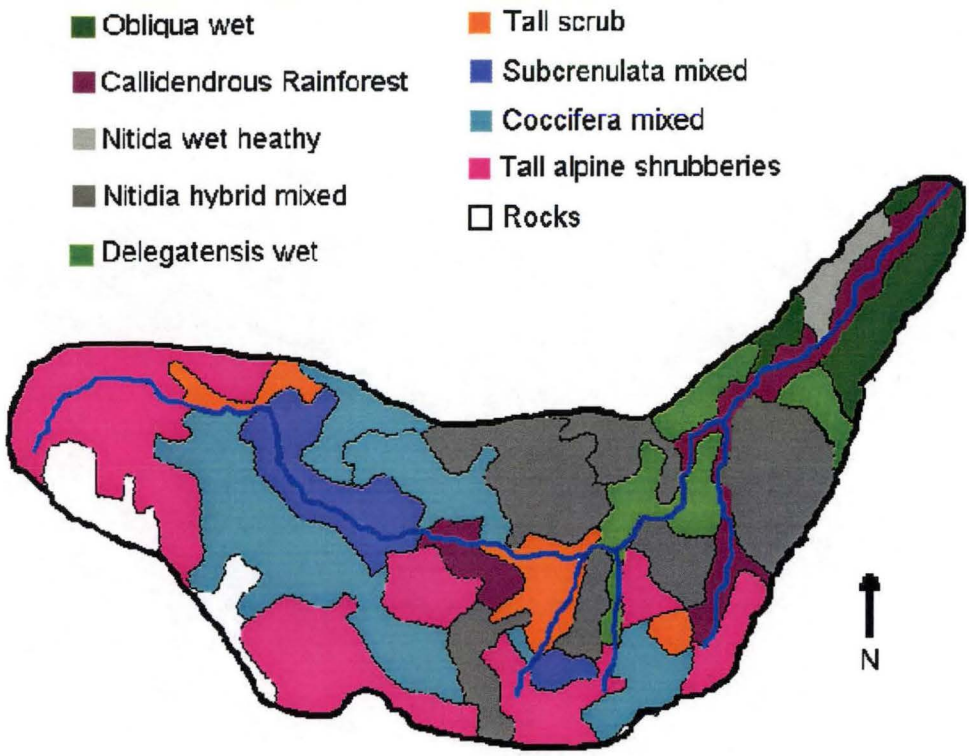
In the Warra Creek catchment, vegetation along the rivercourse consists of Implicate rainforest (dense, tangled, and structureless), with wet *E. obliqua* dominating the lower parts of the catchment. At about 450 metres this gives rise to wet and mixed *E. delegatensis*. Above and around this site, where a shelf of Permian sedimentary rocks occurs, *E. nitida* wet, and a low scrub moorland complex dominates the vegetation. The top of the catchment contains *E. nitida* in a 6 metre canopy over *Banksia* and tall *Leptospermum nitidum* with *Gahnia*, *Calorphus* and *Bauera* beneath. Swampy openings occur in this vegetation and are dominated by *Melaleuca squamea* (Figure 5.7) (Corbett 1997).

Figure 5.7: Vegetation of Warra Creek catchment (modified from Corbett, 1997).



The vegetation along the rivercourse in Crystal Creek catchment is Callidendrous rainforest, wet *E. obliqua* dominates the lower parts of the catchment. At about 450 metres *E. obliqua* changes to wet *E. delegatensis*, above and around this the vegetation is dominated by *E. nitida* wet hybrid. The top of the catchment contains mixed *E. coccifera* and tall alpine shrubberies (Figure 5.8).

Figure 5.8: Vegetation of Crystal Creek catchment catchment (modified from Corbett, 1997).



5.6 Soils

Information on the spatial distribution of soils in the Warra LTER site is sparse. The soils have not been systematically mapped, although Laffan (2002) recently presented some generalised information on dolerite soil properties. Soil patterns are described as highly diverse and reflect marked variation due to the environmental factors of geology, vegetation, topography and to a lesser extent rainfall. Where the vegetation cover is comprised of heath or scrub, organic soils characterised by reddish-black fibrous peat are found. Under forests, mineral soils with gradational texture-profiles are prevalent (Laffan 2002). Geology plays a major role in determining soil characteristics and together they show clear links to the type of natural vegetation occurring in the area (Laffan 2002). Two distinct soil types are found in Warra and Crystal Creek catchments.

Soils on Permo-Carboniferous rocks and derived Quaternary slope deposits comprise sedimentary rocks of the Parmeener Supergroup and include mudstone, siltstone and tillite. These types of rocks produce soils ranging from moderately well drained with

high erodibility and low nutrient status to soils with impeded drainage, higher nutrient levels and lower erodibility.

Soils on Jurassic dolerite and Quaternary deposits from dolerite are divided into two types, those at high elevation under alpine vegetation (heath, scrub and herbfields) and soils at mid and low elevation under wet forest. The soils under alpine vegetation are generally shallow and extremely stony and often occur with scree slopes. Surface layers frequently comprise fibrous peats overlying shallow loamy subsoil. Nutrient levels are low. Soil under wet forests exhibit a wide range of stoniness and depth to bedrock with a wide range of drainage patterns. This is dependent on the elevation and slope of the area.

The dolerite soils are mostly well-drained soils (56 per cent), with some imperfectly drained soils (32 per cent) and a minor amount of poorly drained soils (12 per cent). Clear links between drainage and vegetation were recorded during the soil transects. Well-drained soils had a cover of *Banksia marginata*, imperfectly drained soils had a cover of *Gahnia grandis* and poorly drained soils supported tea-trees (*Leptospermum* spp. and *Melaleuca* spp.) The poorly drained soils were found mainly in shallow depressions or small hollows, whereas steeper slopes and undulating terrain supported freely draining soils. There was a statistical significance in two properties between the well-drained and poorly drained soils. The well-drained soils contained higher total phosphorus and lower exchangeable magnesium levels. Overall the surface of dolerite soils were found to be strongly acidic (pH < 5.0) with high levels of total nitrogen (> 0.2 per cent) and organic carbon (> 5.0 per cent) and medium levels of total phosphorous (0.010 – 0.025 per cent) (Laffan 2002).

5.6.1 Classification of soil types found in Warra Creek catchment

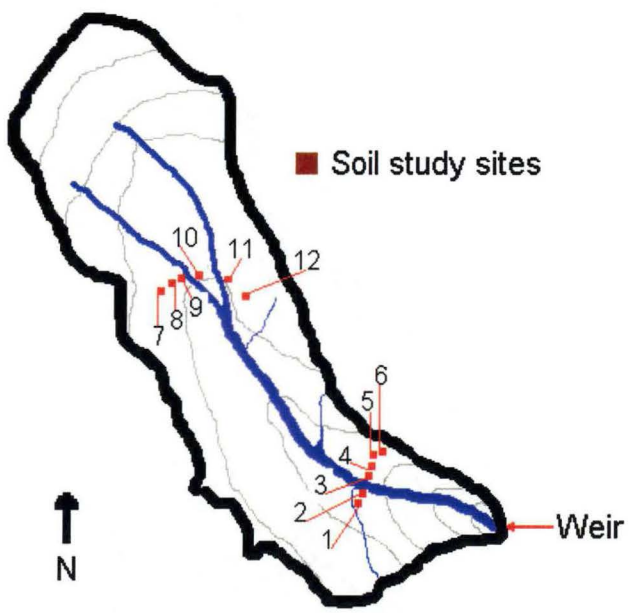
To gain a better understanding of the soil-water interactions occurring in Warra Creek catchment, profile descriptions and classification of soils were conducted, resulting in the production of a soil map (Figure 5.10). Twelve soil and site surveys forming two transects across the catchment (Figure 5.9) were completed, each study sites specific location and altitude are discussed in Table 5.2. Appendix 2 describes specific soil profiles for each site surveyed. Three distinct soil types were found in the Warra catchment, two types, organic and red brown clayey soils were classified

from Jurassic dolerite, while the third, yellowish brown sandy soils were located on Permian sandstone, siltstone and mudstone.

Table 5.2: Soil study site locations and altitudes.

Site	Easting	Northing	Altitude (metres)
1	0475221	5231290	460
2	0475221	5231290	460
3	0475221	5231290	470
4	0475221	5231290	470
5	0475221	5231290	460
6	0475279	5231369	460
7	0473919	5232297	600
8	0474013	523409	570
9	0474013	5232406	550
10	0474013	5235406	550
11	0474198	5232534	550
12	0473920	5232295	530

Figure 5.9: Warra Creek catchment displaying soil study sites.



5.6.1.1 Organic soil under wet forest and scrub

This soil is an accumulated organic layer with some mineral material from adjacent soils (Table 5.3 and Plate 5.1). The organic soil is located on steep gorges of well drained Jurassic dolerite in high rainfall areas of the southern forests. Vegetation on this soil consists of open mixed forest with understorey rainforest (Plate 5.2). Species include *Atherosperma moschatum, Eucryphia lucida, Gahnia grandis, Nothofagus*

cunninghamii, Anodopetalum biglandulosum, Blechnum nudum, Telopea truncata and occasional large Eucalypt species.

On recently burnt sites there is no organic layer, just a covering of moss on the rocks. Depth of the organic soil layer varies from zero to up to 1 metre, depending on slope and fire history. The 'soil' is of low bulk density and has little strength to support large erect trees. In stable rocky areas a mixture of peat and boulders form the soil matrix. Along stream beds this layer accumulates above the stream, often suspended by roots and scrub, particularly horizontal, and it forms a 'soil' above the ground surface. This 'soil' is interspersed with pockets of mineral where erect trees grow (e.g., site five).

Table 5.3: Typical soil profile description of organic soils on Jurassic dolerite.

Horizon	Depth (cm)	Description
O1	-31 to -30	Loose litter and leaves from understorey plants and ferns
O2	-30 to 0	Dark reddish brown (2.5YR2.5/3 grading to 10YR2.5/3) organic material with some mineral soil and abundant roots. Sapric to sandy peat. Very light material.

Plate 5.1: Typical profile of organic soil on Jurassic dolerite.

Plate 5.2: Typical vegetation associated with organic soils on Jurassic dolerite.

5.6.1.2 Red brown clayey soils under wet forest and scrub

This is a gradational soil with an organic surface (Plate 5.3 and Table 5.4). The red brown clayey soil is located on hills and steep gorges of well to medium drained Jurassic dolerite in high rainfall areas of the southern forests. Vegetation on this soil consists of open mixed forest with understorey rainforest (Plate 5.4). Species include large *E. delegatensis* and *E. obliqua*, *Nothofagus cunninghamii, E. nitida, Atherosperma moschatum, Gahnia grandis, Anodopetalum biglandulosum, Leptospermum lanigerum, Cenarrhnes nitida, Telopea truncata, Tasmannia lanceolata, Blechnum nudum* and *Eucryphia lucida.*

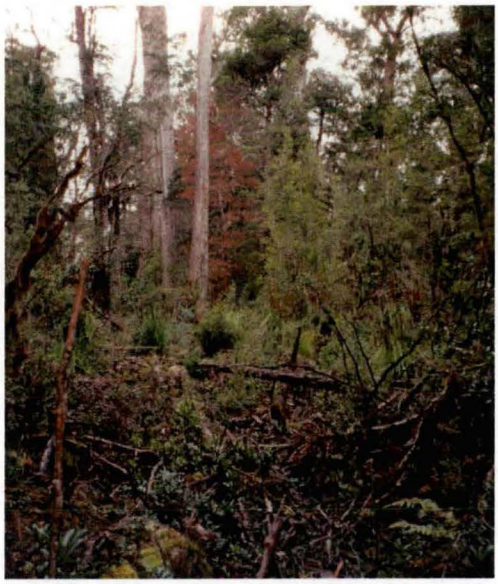
The A1 horizon is often absent, with an abrupt transition from organic horizon into surface mineral horizon characteristic of the B horizon. On warmer sites at the Warra LTER area a significant A1 horizon of about 10 centimetres thickness has developed (Laffan, 2002). Subsoil colours vary from dark red to dark yellow brown. Stoniness is highly variable but rounded cobbles of 200 millimetres diameter are common in the subsoil. Soils may be shallow (30 – 40 centimetres) and large trees develop broad plate-like root systems. On drier slopes species such as the eastern side of Warra Creek, celery-top pine, waratah and cutting grass are more abundant. On the better soils dense productive forest develops and soils are deep. Iron oxide and organic cutans are present in some B2 horizons.

Plate 5.3: Typical profile of red brown clayey soils under wet forest and scrub.

Table 5.4: Typical soil profile description of red brown clayey soils under wet forest and scrub.

Horizon	Depth (cm)	Description
O1	-5 to -3	Loose litter and leaves from understorey plants and fern
O2	-3 to 0	Dark reddish brown (5YR3/3) organic material with some mineral soil and abundant roots.
B1	0 to 30	Yellowish red (5YR5/6) silty-clay loam. Weak strength. Abundant roots and a gradational boundary
B2	30 to 60	Strong brown (7.5YR5/6) light clay. Weak strength. Some structure with 20- 50 mm polyhedral peds. Abundant roots, diffuse boundary and dolerite fragments.
B3	60 to 70	Strong brown (7.5YR5/8) light clay on top of bedrock. Weak strength, abundant roots, abrupt boundary and dolerite fragments.

Plate 5.4: Typical vegetation associated with red brown clayey soils under wet forest and scrub.



5.6.1.3 Yellowish brown sandy gley soils under wet forest and scrub

This soil consists of an organic surface grading to a gley soil from 28 centimetres depth (Table 5.5) which is saturated for most of the time. In better drained sites there may be 50 centimetres of soil above the gley layer. The yellowish brown sandy soil is located on hills and plateaus of poorly drained Permian mudstone, in high rainfall areas of the southern forests. Vegetation on this soil consists of mixed mooreland scrub (Plate 5.5); large eucalypts do grow on these areas, but only as a sparse forest with extensive shallow root systems. Species include *Leptospermum nitidum, Leptospermum lanigerum, Gahnia grandis, Baloskion tetraphylum, Baurera rubiodes, Grevillea australis vars, Cenarrhnes nitida, E. nitida,* and *E. johnstoni.*

Table 5.5: Typical soil profile description of yellowish brown sandy gley soils under wet forest and scrub.

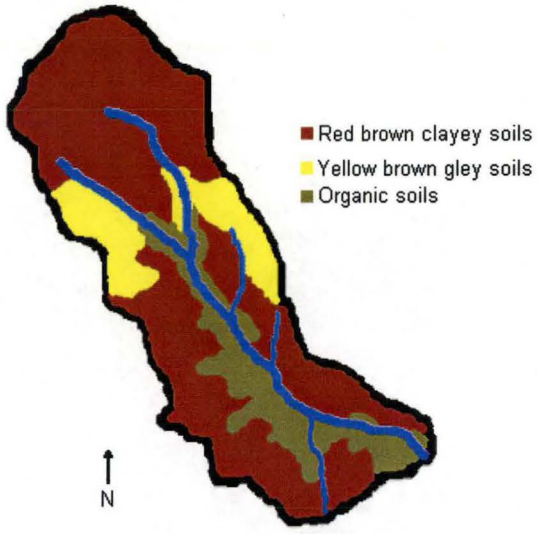
Horizon	Depth (cm)	Description
O1	-5to -3	Loose litter and leaves from understorey plants
O2	-3 to 0	Very dark greyish brown organic material with abundant roots
A	0 to 8	Very dark greyish brown gravelly loam (10YR3/2) with some quartz gravel present. Weak strength, abundant roots and an abrupt boundary

Horizon	Depth (cm)	Description
B21	8 to 15	Dark yellowish brown grading to very dark greyish brown gritty loam (10YR4/4 grading to 10YR3/2). Weak strength, abundant roots and a diffuse boundary
B22	15 to 28	Dark yellowish brown gritty loam (10YR3/3) with very dark (10YR4/4) mottles. Weak strength abundant roots and a diffuse boundary
B22g	28 to 80+	Light greenish grey gley (10Y7/1) grading with increasing depth to greenish grey (10B6/1 and 10Y6/1) sandy loam and then increasing to light clay with further depth. Weak strength increasing with depth, occasional coarse roots.

Plate 5.5: Typical vegetation associated with yellowish brown sandy gley soils under wet forest and scrub.

The soil and associated vegetation survey of Warra Creek catchment resulted in the production of a soil type map (Figure 5.10). If the location of water sampling sites (Figure 5.3) is overlaid onto the soil map, environmental differences between sites can be assessed.

Figure 5.10: Warra Creek catchment soil type map.



5.7 Altitude and topography

Warra Creek catchment faces south and lies on the top plateau on Mount Frederick (Figure 5.11), ranging in altitude from 350 -700 metres (Figure 5.12). Crystal Creek catchment faces east and drains Mount Frederick and the Mount Weld ridge (Figure 5.11) with an altitude ranging from 350 metres to 1100 metres (Figure 5.12). Landscape positioning was used to create a map displaying the locations and topography of both catchments in relation to the surrounding landscape. Warra Creek catchment begins with a moderate slope that quickly flattens out, while Crystal Creek catchment slowly inclines to about 800 metres and then rises steeply towards the top of Mount Weld.

Figure 5.11: Landscape positioning of Warra and Crystal creek catchments.

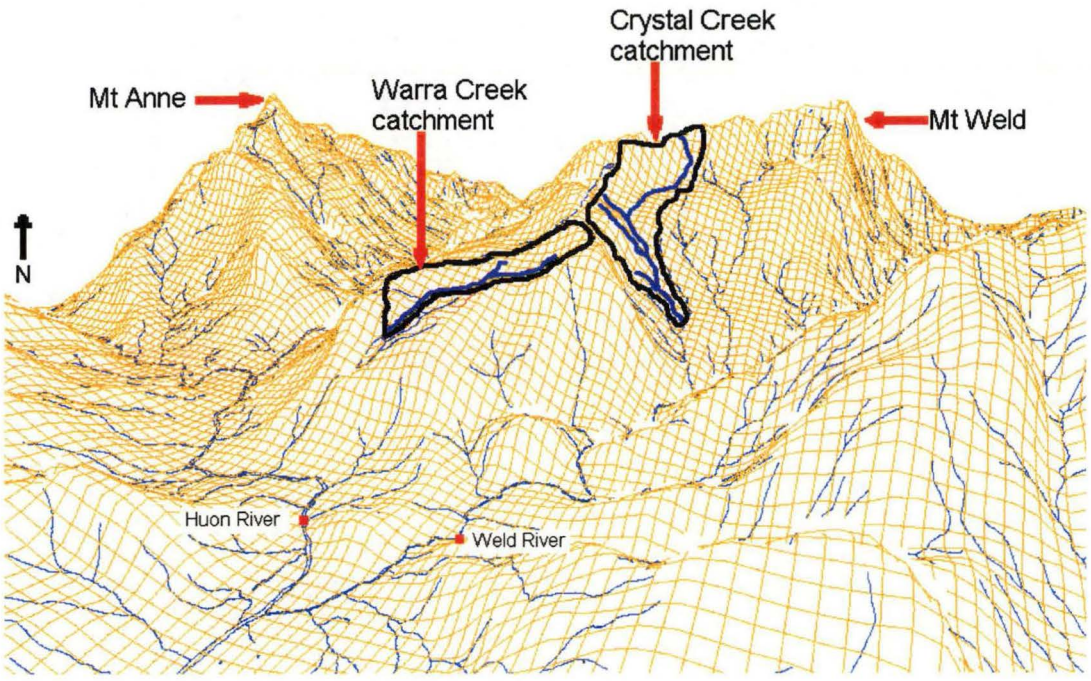
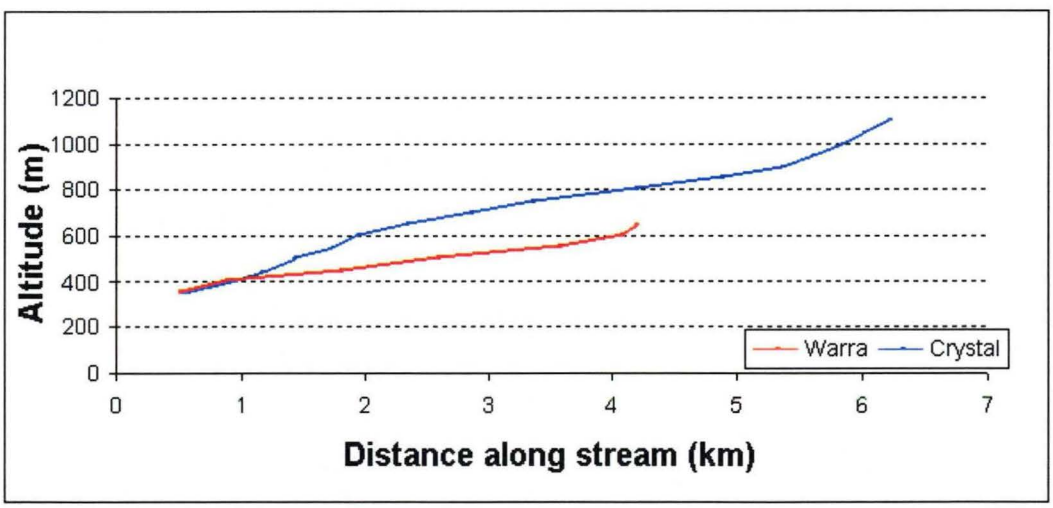


Figure 5.12: Warra and Crystal creek catchment topography.



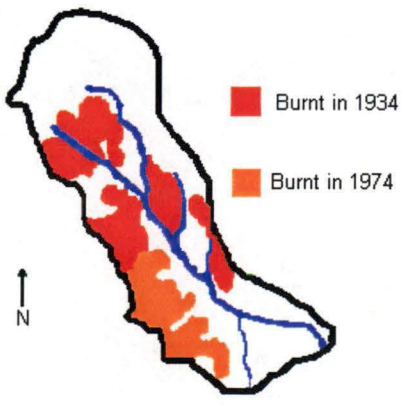
5.8 Fire

Transition of sedgeland to rainforest vegetation is strongly related to time since last fire (Jackson and Brown 1999). In aerated sedgeland-heath Jackson and Brown (1999) recognised three intensity stages that produced vegetation responses:

1. light fires consuming surface plant material resulting in a return of the same vegetation;
2. moderately intense fire consuming vegetation and surface layers of peat resulting in elimination of the previous characteristic species and a temporary replacement by light demanding shrubs; and
3. very intense fires, consuming most of the peat profile down to rocky substrate, resulting in a more permanent change to *Leptosperma filiforme* dominated vegetation.

Research by Hickey et al. (1998) reconstructed the fire history of the Warra LTER by analysing tall wet eucalypt stands through ring counts, from newspaper accounts, historical accounts and aerial photographs. The results indicate a very large intense fire occurring in Tasmania in 1934, estimated to have affected more than a third of Tasmania's land area. This fire affected the Warra LTER area, resulting in burning of the middle to upper portion of Warra Creek catchment (Figure 5.13) (Hickey et al. 1998). When fire history maps are overlaid onto vegetation maps, vegetation patterns emerge which suggest a reaction to the fire. Where fire has burnt areas in Warra Creek catchment there are now large areas of *E. nitida* wet, with some low scrub/mooreland (water sample sites 1 and 2) (Figure 5.7). This vegetation pattern reflects the vegetation response proposed by Jackson et al. (1999), which results in a change from rainforest species to more light demanding species. Crystal Creek catchment has remained unburnt since at least 1850 and possibly longer (Hickey et al. 1998).

Figure 5.13: Warra Creek catchment fire history.



5.9 Summary

The location and topography of the two catchments with their associated study sites are mapped in this chapter, along with descriptions of geology, vegetation and soil types found within each catchment. Warra Creek catchment is relatively flat, faces a southerly direction, and is composed of Jurassic dolerite with some Permian sedimentary rocks and a range of soils (soil type depends on environmental factors). Vegetation is composed of mixed forests at lower altitudes grading with altitude to low scrub mooreland (associated with recent fires). Crystal Creek catchment is moderately steep, faces easterly and is composed of Quaternary talus dominated by Jurassic dolerite boulders with some Permian sedimentary sequences. Vegetation is also mixed forest in the lower altitudes grading to alpine shrubberies.

Chapter 6: Fortnightly water sampling results

6.1 Introduction

Water quality data collection consisted of three separate methods designed to encompass the range of conditions that occurred through the year of 2001. This chapter outlines flow rates of Warra Creek, rainfall data from the Warra LTER area and fortnightly water sampling results from Warra and Crystal creeks.

6.2 Stage heights of Warra Creek

The stage height of Warra Creek was measured continuously at a "V" notch weir. Data are divided up into seasons to illustrate changes in stream heights occurring throughout the sampling year. Water sampling collection times for the three separate data collection methods are highlighted on the seasonal graphs (Figures 6.1, 6.2, 6.3, and 6.4).

Stage heights for the summer period are displayed in Figure 6.1. During this season baseflow water levels were about 100 millimetres above the "V" notch in the weir and no significant storm events occurred. A decreasing water table resulted in a gradual decline in creek height at the weir. Catchment snapshot sampling was conducted during one baseflow period (indicated as chemical analysis).

Figure 6.1: Summer stage height and water sampling periods.

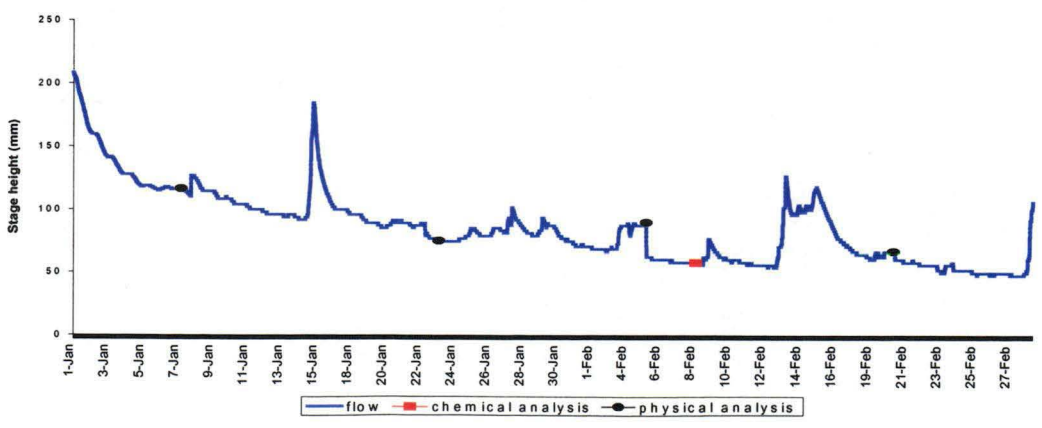


Figure 6.2 displays the stage heights for autumn, where levels gradually increased between storm events to between 100 and 200 millimetres above the "V" notch. Several storm events occurred during this season, the largest of which was sampled. Catchment snapshot sampling was conducted during one baseflow period. Storm events on average lasted two to three days. A small gap in the data was due to malfunctioning equipment.

Figure 6.2: Autumn stage height levels and water sampling periods.

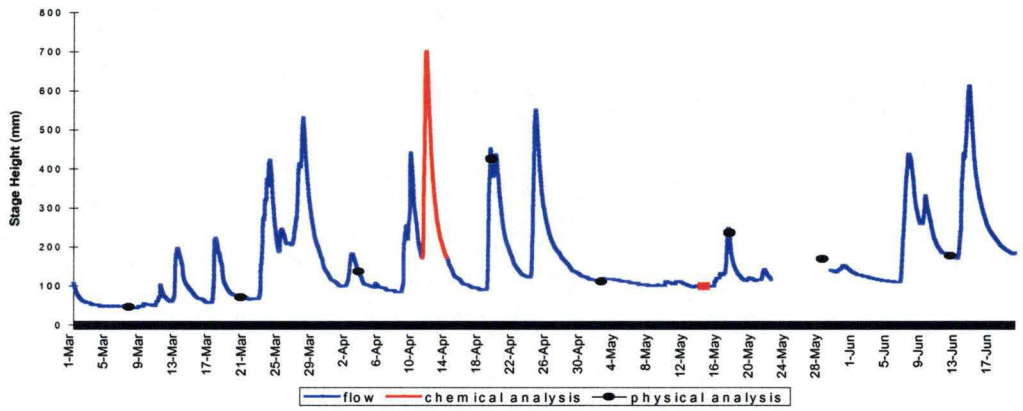


Figure 6.3 displays the stage height for winter where creek levels gradually increased between storm events to around 200 millimetres above the "V" notch. Four storm events occurred during this season, none of which were intensively sampled. Catchment snapshot sampling was conducted during one baseflow and one highflow period. Storms on average lasted three to four days, with one very significant storm event that was a combination of several successive rain events.

Figure 6.3: Winter stage height levels and water sampling periods.

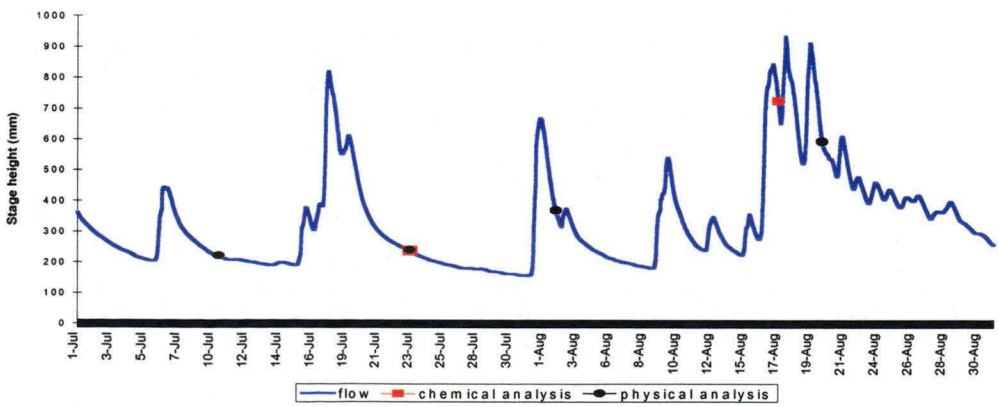
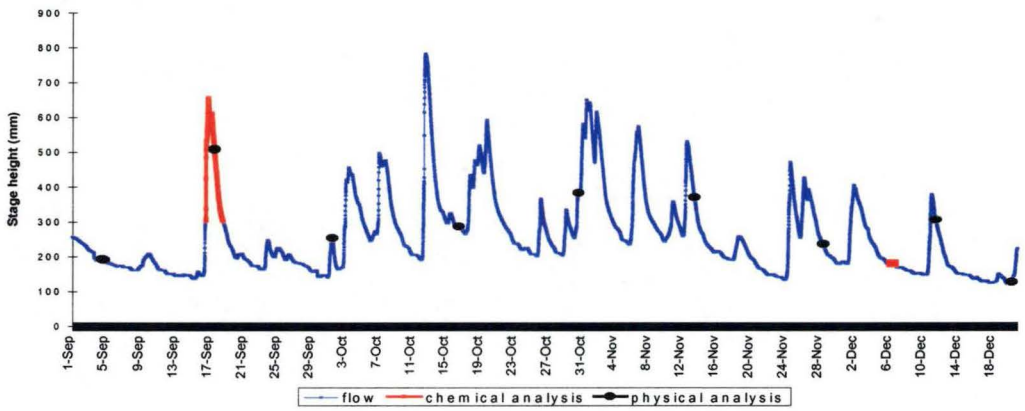


Figure 6.4 displays the stage height for spring where creek levels remained at the high level of 200 mm above the "V" notch. High baseflow levels remained due to an unusually wet spring, as seen by the very numerous storms. The first storm event after a relatively settled period was intensively sampled for water analysis. Catchment snapshot sampling was conducted during one baseflow period towards the end of spring. Storm events on average lasted two to three days.

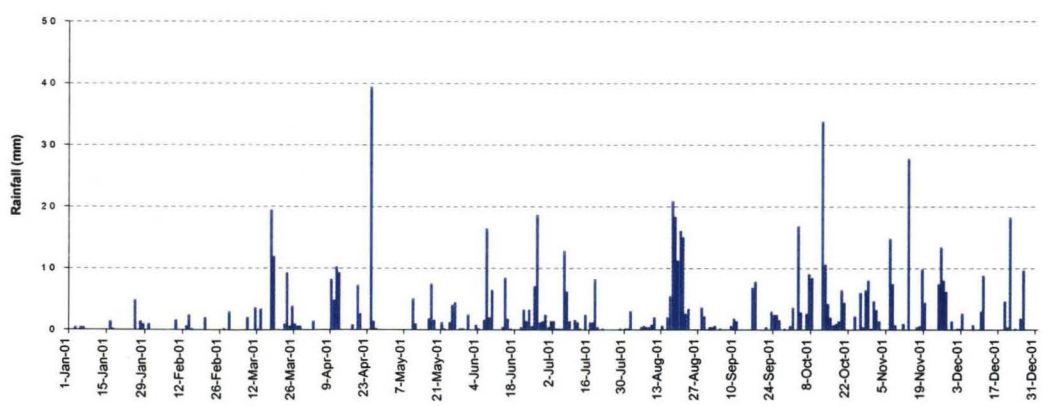
Figure 6.4: Spring stage height levels and water sampling periods.



6.3 Rainfall

Rainfall data were obtained from the most representative weather station in the area, located in Grove. However, the Grove Research Bureau of Meteorology Weather Station (42° 59'06 S, 147° 04'30 E) (Figure 6.5) is in a considerably drier location than the Warra LTER site. Rainfall for 2001 was considered average, but rain for the first half of the year was below average while for the second half it was slightly above average. A total of 746 millimetres of rain fell at Grove in 2001.

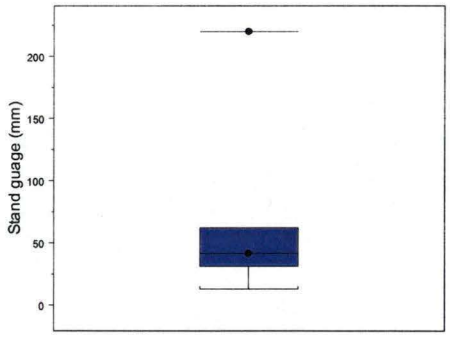
Figure 6.5: Daily rainfall data (2001) at the Grove Research Bureau of Meteorology Weather Station.



The rainfall data collected from Grove, while not exactly the same as that found in the Warra LTER site, highlight times of increased daily rainfall and display the general trend of rainfall. Figure 6.5 indicates several extreme fall events such as those of 24 April, 15-20 August and the 23-24 November. These extreme fall events and the general rainfall trends are all reflected in the stream height graphs of Warra Creek (Figures 6.1, 6.2, 6.3 and 6.4).

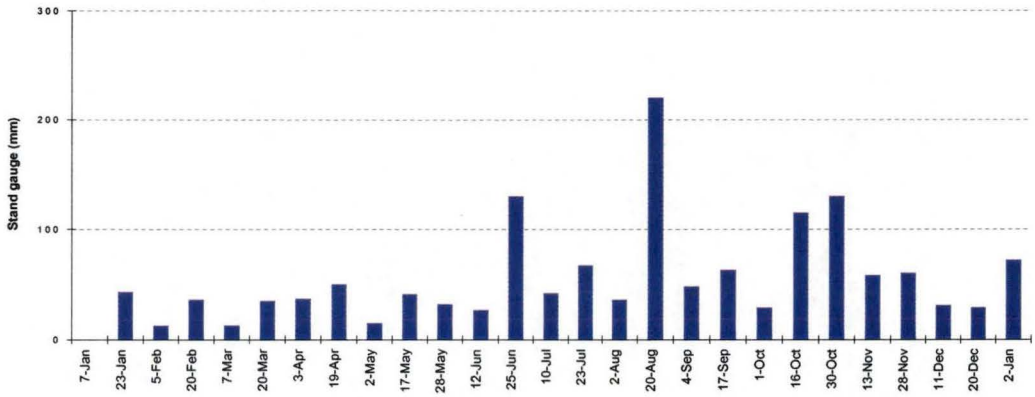
To complement the Grove data, rainfall was also collected from a stand gauge near Warra Creek (Figure 6.6 and 6.7, Appendix 3). The stand gauge was emptied on fortnightly water sampling days. Total rainfall collected from the stand gauge in 2001 was 1335 millimetres. The stand gauge measurements from Warra Creek displayed in Figures 6.6 and 6.7 highlight a limited distribution of data, with some extreme outlying rainfall events. Rainfall across the year was very consistent with a median recorded rainfall per fortnight of 41.5 millimetres.

Figure 6.6: Summary statistics from fortnightly data collected for stand gauge rainfall measurements at the Warra LTER site.



Significant strong positive correlations between stand gauge measurements and stage height at Crystal Creek (r^2= 0.749, P < 0.0002) and Warra Creek (r^2= 0.765, P < 0.0001) were found. This indicates that the generation of flow rates in these particular creeks is directly controlled by the amount of rain falling at the Warra LTER site.

Figure 6.7: Stand gauge rainfall heights for fortnightly measurements during 2001 at the Warra LTER site.

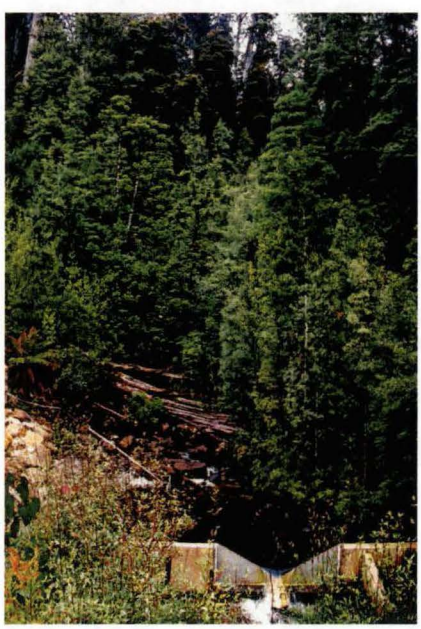


6.4 Fortnightly water quality monitoring

Fortnightly sampling was carried out at two sites, Warra Creek weir and Crystal Creek (Appendices 4 and 5). The location for both sites are shown in the catchment maps in Figures 5.3 and 5.4, with grid references for the sites located in Table 5.1. Plates 6.1 and 6.2 display the two creeks at low flow. These pictures highlight the vegetation differences between the two sites, with Crystal Creek appearing as a drier site to Warra Creek.

Plate 6.1: Crystal Creek.

Plate 6.2: Warra Creek.



6.4.1 Water flow levels

Creek levels were recorded from a stage height board at Crystal Creek and the height above the "V" notch weir at Warra Creek for each fortnightly water sample collected (Figure 6.8). Figures 6.8 and 6.9 display the range of water levels encompassed by this fortnightly sampling program.

Figure 6.8: Fortnightly stage gauge heights in Warra and Crystal creeks during 2001.

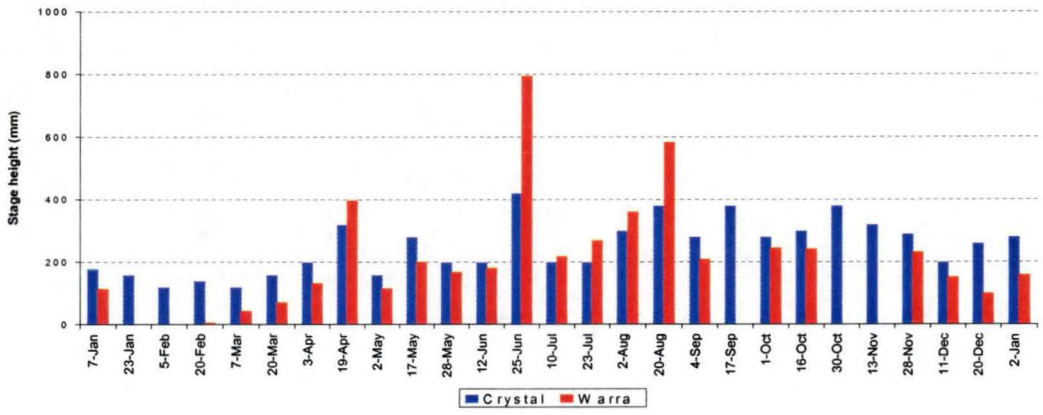
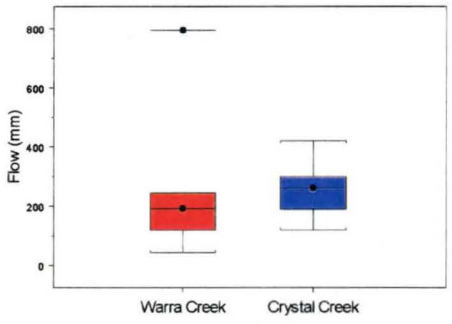


Figure 6.9: Summary statistics from fortnightly data collected for stage gauge heights in Warra and Crystal creeks.



Summary statistics emphasize the small range of water levels in the two creeks. These creeks during both wet and dry periods maintain good baseflow levels of water, with median stream heights of 191.5 millimetres at Warra Creek and 260 millimetres at Crystal Creek. However, Warra Creek displays a much higher maximum stream height, indicating a strong pulsed flow caused by increased runoff during the two largest storm events for the year (25th June and 20th August).

There was a significant very strong positive correlation between flow rate at Crystal and Warra Creek ($r^2 = 0.858$, $P < 0.0001$). This is important because it means Warra

Creek and Crystal creeks are controlled by similar rainfall patterns and can therefore be used as comparison for the assessment of other factors.

6.4.2 Physical parameters

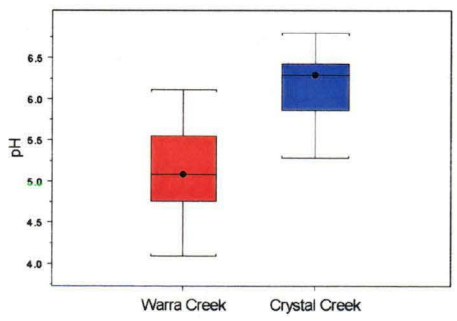
The fortnightly samples were analysed for pH, electrical conductivity, turbidity and temperature (Figures 6.11, 6.12, 6.15 and 6.17). In both creeks, stage height was found to be significantly positively correlated with turbidity, and negatively correlated with conductivity (Crystal Creek only), pH and temperature.

6.4.2.1 Hydrogen ion

In the Warra catchment, pH had a median level of 5.1 (Figure 6.10). However, pH levels range between 4.1 and 6.1 throughout the year. A very strong negative correlation exists between pH and stage height (r^2 = -0.834, $P < 0.0001$) and a moderate negative correlation with pH and stand gauge rainfall (r^2 = -0.595, $P < 0.0072$). This correlation can be easily observed in Figure 6.11, where increased winter flow causes decreased pH levels.

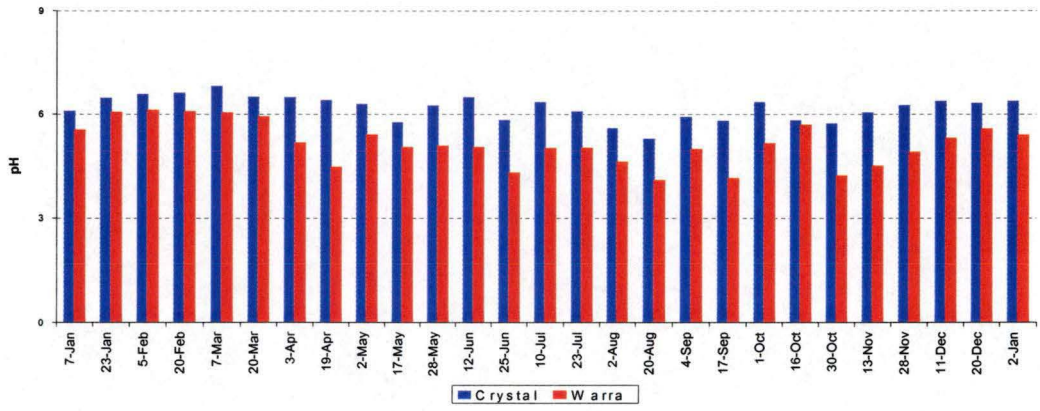
Crystal Creek catchment is slightly different to Warra Creek with the median measurements approaching neutral levels of 6.3, compared to the 5.1 at Warra Creek. However, seasonal trends were similar at Crystal Creek with strong negative correlations between pH and flow (r^2 = -0.799, $P < 0.0001$) and pH with stand gauge rainfall (r^2 = - 0.765, $P < 0.0001$).

Figure 6.10: Summary statistics from pH at Warra and Crystal creeks for fortnightly data collected during 2001.



pH was also positively correlated with conductivity at Warra Creek (r^2 = 0.456, P < 0.496) and at Crystal Creek (r^2 = 0.749, P < 0.0002) and weakly negatively correlated with turbidity (r^2 = -0.467, P < 0.0436) at Warra Creek.

Figure 6.11: Fortnightly changes for pH in Warra and Crystal creeks during 2001.



6.4.2.2 Electrical conductivity

The electrical conductivity of the two creeks shows a distinctive seasonal trend (Figure 6.12), with readings increasing through summer until the first storms in late March (Figures 6.2 and 6.5). Median conductivity levels were very similar between the two creeks although slightly higher at Crystal Creek (Figure 6.13). Crystal Creek also shows a larger distribution of levels ranging from 30.2 $\mu S/cm^{-1}$ in mid winter to 75.7 $\mu S/cm^{-1}$ in late summer.

Figure 6:12 Fortnightly changes for electrical conductivity in Warra and Crystal creeks during 2001.

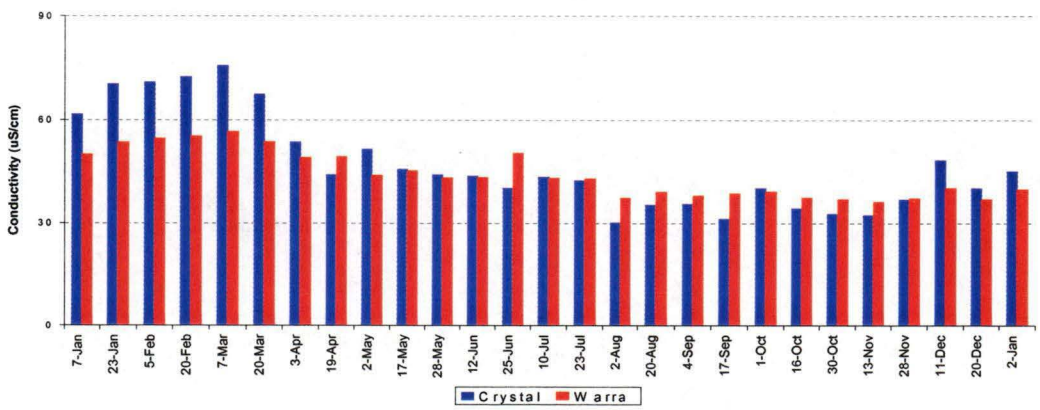
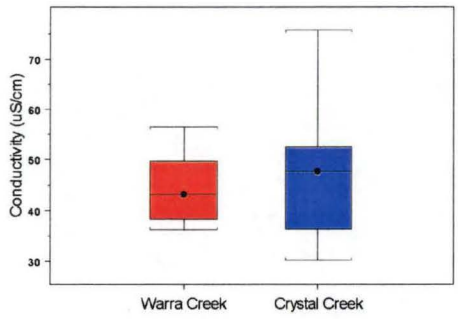


Figure 6.13: Summary statistics for electrical conductivity at Warra and Crystal creeks from fortnightly data collected during 2001.



6.4.2.3 Turbidity

Turbidity in any water is an indication of the amount of suspended material transported by the river at the time of sampling. The fortnightly sampling program gave very low median levels of 1.4 NTU in Warra and 0.5 NTU at Crystal Creek (Figure 6.14). However, when sampling occurred during extreme rainfall events high turbidity readings were collected from both catchments. There is a slight seasonal trend resulting in increased turbidity during the winter months (Figure 6.15), reflected by a strong positive correlation with flow at Warra Creek ($r^2 = 0.748$, $P < 0.0002$) and a moderate positive correlation at Crystal Creek ($r^2 = 0.593$, $P < 0.0074$). A low negative correlation with turbidity and pH at Warra Creek ($r^2 = -0.468$, $P < 0.0436$) also occurred.

Figure 6.14: Summary statistics for turbidity at Warra and Crystal creeks from fortnightly data collected during 2001.

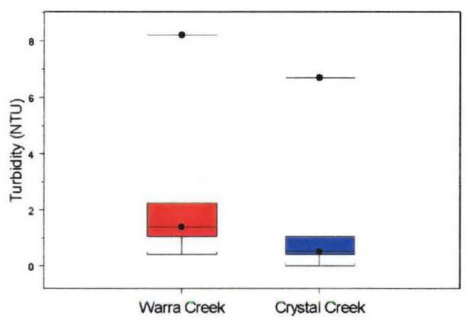
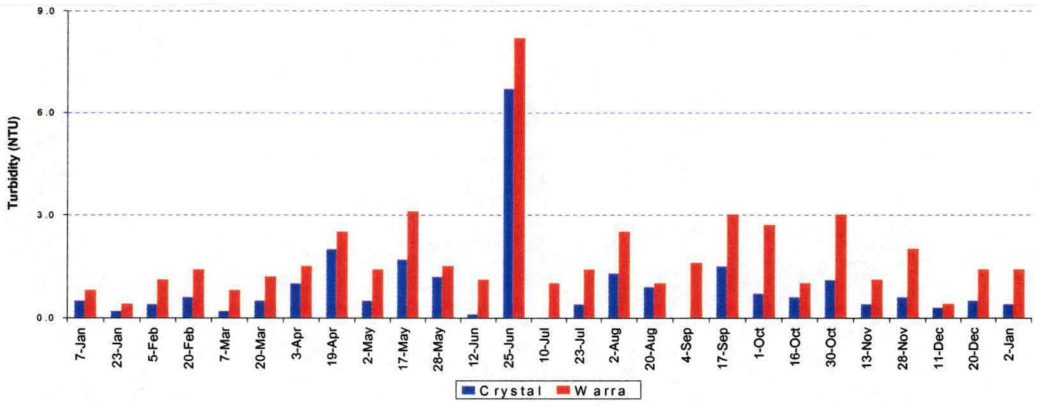


Figure 6.15: Fortnightly changes for turbidity in Warra and Crystal creeks during 2001.



6.4.2.4 Temperature

Water temperature displays a large range of levels in both Warra and Crystal creeks, with Warra Creek having a slightly warmer median temperature of 7°C, compared to Crystal Creeks median temperature of 7.8 °C (Figure 6.16). There is a distinct seasonal profile in both streams of warmer in summer and cooler in winter (Figure 6.17).

Figure 6.16: Summary statistics for temperature at Warra and Crystal creeks from fortnightly data collected during 2001.

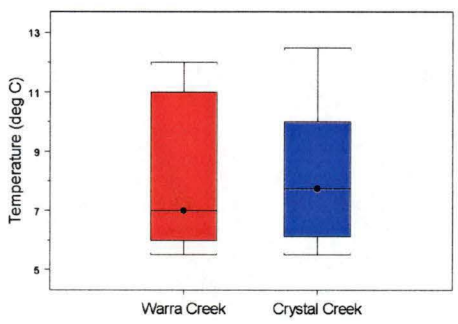
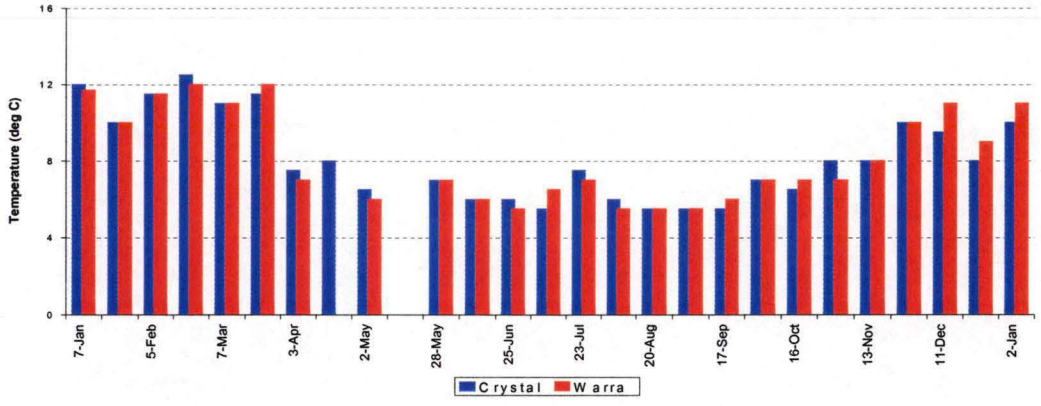


Figure 6.17: Fortnightly changes for temperature in Warra and Crystal creeks during 2001.



6.4 Summary

In 2001 there was a consistent spread of rainfall on both Warra and Crystal creek catchments. A strong significant positive correlation was found between stage height of the two creeks. Stage height was also significantly positively correlated with rainfall and turbidity and significantly negatively correlated with pH, temperature and conductivity (Crystal Creek only).

An obvious increase in pH, temperature and conductivity occurs from mid-winter onwards, culminating in peaks towards the end of summer. Turbidity is directly correlated with stage height and therefore exhibits an opposite pattern to the other measured parameters. Water temperature is most likely higher in Crystal Creek because its aspect faces east while Warra faces south, resulting in increased sunlight to the Crystal Creek catchment. Crystal Creek has slightly higher median levels for temperature, pH and conductivity, with lower turbidity levels. The two creeks have therefore displayed very similar results during the fortnightly water sampling program.

Chapter 7: Catchment "snapshot" water sampling results

7.1 Introduction

Results from the catchment "snapshot" water sampling regime that occurred at summer, winter and spring baseflow levels and during one winter high flow level (storm) are analysed and discussed in this chapter. This sampling regime analysed water for all parameters at five locations in Warra Creek and one location at Crystal Creek (Appendices 6 and 7). Table 5.1 and Figures 5.3 and 5.4 detail the location of these sites. Each snapshot sampling site contains different environmental aspects that affect water quality entering the creek, geology, soil types, vegetation and creek descriptions are discussed to assist in the analysis of results.

All parameter levels were analysed with a box and whisker plot displaying each sampling location. For each parameter (except pH and electrical conductivity), median levels per hectare above each sampling site are presented in a bar graph (i.e., median measurements at each sampling site are divided by the total catchment area upstream of each sample point).

This method of analyses based on the Horton Model (Chapman 1996) assumes all parts of the catchment contribute equally to surface run-off. However, Elsenbeer (2001) demonstrated that during baseflow periods only a small percentage of the catchment contributes to flow. This technique therefore, while not perfect, does provide a method for comparing differences in parameter levels between sites, based on their potential contributing catchment sizes. Median levels of parameters can then be assessed as accumulated contributions per hectare, thus allowing for an indication of a point or diffuse source.

7.2 Catchment snapshot sampling sites

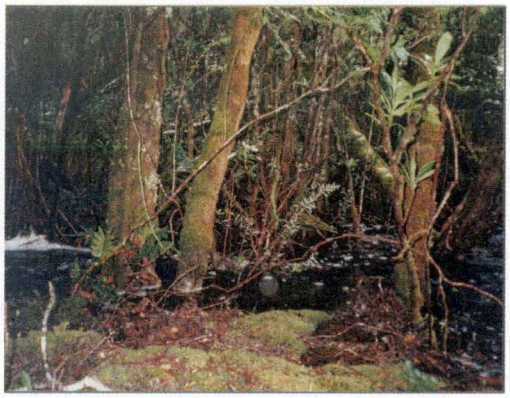
7.2.1 Site one

Site one has 124.9 hectares of contributing catchment area and was located on the top right tributary of Warra Creek, on relatively flat ground (Plates 7.1 and 7.2). This site

has a sandy bottom is about 1 metre across and surrounded by a mossy bank. Geology is a mixture of Jurassic dolerite and Permian sedimentary rock (Figure 5.5). Vegetation consists of implicate rainforest, surrounded by *Eucalyptus nitida* wet and *E. nitida* hybrid mixed (Figure 5.7) Plant species present include *Atherosperma moschatum, Nothofagus cunninghamii, Cenarrhnes nitida, Anodopetalum biglandulosum* and *Blechnum nudum.*

Plate 7.1: Site one at baseflow levels.

Plate 7.2: Site one at high flow levels.



7.2.2 Site two

Site two has 52.7 hectares of contributing catchment area and was located on the top left tributary of Warra Creek, on relatively flat ground (Plates 7.3 and 7.4). This site has a sandy bottom, is about 1 metre across and densely covered by vegetation. Geology and soil are the same as site 1. Vegetation consists of implicate rainforest, surrounded by low scrub moorelands, *E. nitida* wet and *E. nitida* hybrid mixed (Figure 5.7) Plant species present include *Atherosperma moschatum, Nothofagus cunninghamii, Gahnia grandis, Cenarrhnes nitida, Anodopetalum biglandulosum, Leptospemum nitidum* and *Blechnum nudum.*

Plate 7.3: Site two at baseflow levels.

Plate 7.4: Site two at high flow levels.

7.2.3 Site three

Site three has 282.4 hectares of contributing catchment area and was below the influence of all the major tributaries into Warra Creek, on slightly sloping ground (Plate 7.5). This site has a rocky bottom 1.5 - 2 metres across, woody debris in the creek channel and is covered by dense vegetation. Geology between this site and site 1 and 2 is Jurassic dolerite (Figure 5.5). The creek bed contains organic soils, with red brown clayey soil in the surrounding area (Figure 5.9). Vegetation consists of implicate rainforest, surrounded by mixed *E. delegatensis* and *E. obliqua* forest (Figure 5.7). Plant species present include; *Gahnia grandis, Leptospemum nitidum, Atherosperma moschatum, Nothofagus cunninghamii, E. obliqua, Cenarrhnes nitida, Anodopetalum biglandulosum* and *Blechnum nudum.*

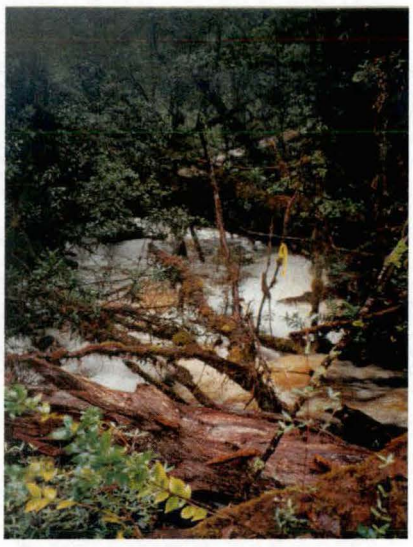
Plate 7.5: Site three at baseflow levels.

7.2.4 Site four

Site four has 311.5 hectares of contributing catchment area and was below the influence of all the major tributaries into Warra Creek, halfway between site 3 and the weir site, in a steep gully (Plates 7.6 and 7.7). This site has a rocky bottom, with rock pools, 2-3 metres across, is covered by woody debris and has a build up of silt above the debris and rocks. Geology and soils are the same as site 3. Vegetation is open mixed implicate rainforest, surrounded by wet *E. obliqua* forest (Figure 5.7). Plant species present include *Eucryphia lucidia, Gahnia grandis, E. obliqua, Atherosperma moschatum, Nothofagus cunninghamii, Anodopetalum biglandulosum* and *Blechnum nudum.*

Plate 7.6: Site four at baseflow levels.

Plate 7.7: Site four at high flow levels.



7.2.5 Warra Creek weir site

Warra Creek weir site has 412 hectares of contributing catchment area and was below the influence of all the major tributaries, in a steep gully (Plate 7.8 and 7.9). This site has a rocky bottom, numerous rock pools, 3-4 metres across and is covered by woody debris in the creek channel. Geology and soils are the same as site 3. Vegetation is open mixed implicate rainforest, surrounded by wet *E. obliqua* forest (Figure 5.7). Plant species present include *Eucryphia lucidia, E. obliqua, Atherosperma moschatum, Nothofagus cunninghamii* and *Blechnum nudum.*

Plate 7.8: Weir at baseflow levels.

Plate 7.9: Weir at high flow levels.

7.2.6 Crystal Creek site

Crystal Creek site has 550 hectares of contributing catchment area and was below all the major tributary influence, on relatively flat ground (Plate 7.10 and 7.11). This site has a rocky bottom, numerous rock pools, 4-5 metres across, and is covered by

woody debris in the creek channel. Geology surrounding the sampling site is Permian sedimentary rock. The remaining catchment contains Jurassic dolerite and related rocks. Vegetation is open mixed callidendrous rainforest, surrounded by wet *E. obliqua* forest (Figure 5.7). Plant species present include *Eucryphia lucidia, E. obliqua, Atherosperma moschatum, Nothofagus cunninghamii* and *Blechnum nudum.*

Plate 7.10: Crystal Creek at baseflow levels.

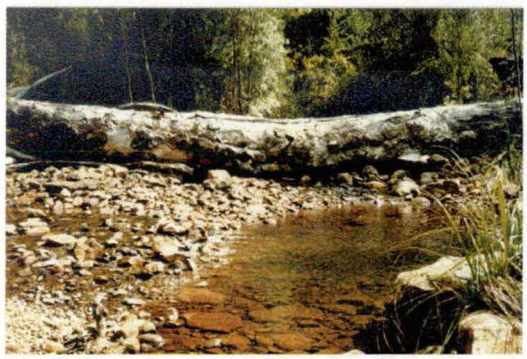


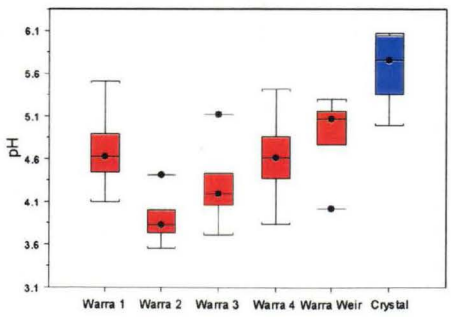
Plate 7.11: Crystal Creek at high flow levels.

7.3 Physical parameters

7.3.1 Hydrogen ion

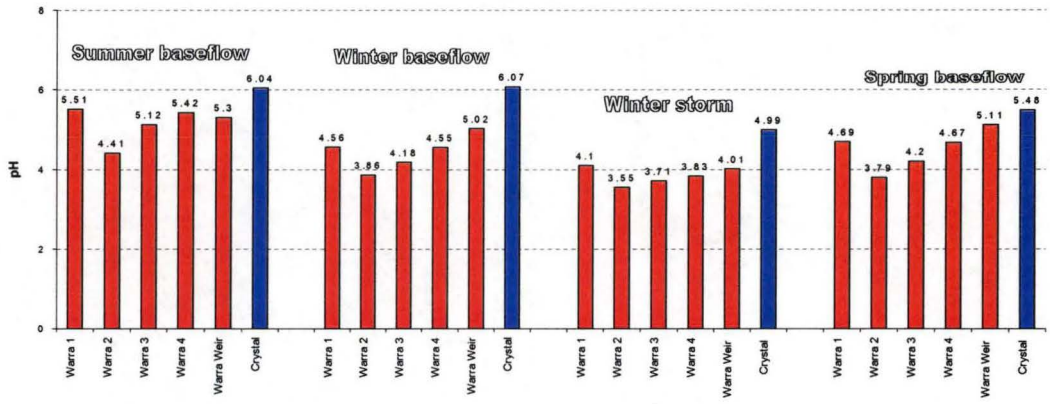
In the Warra Creek catchment all monitored sites had low pH levels. Site 2 was the lowest site with a median pH of 3.8. Site 1 had a median pH of 4.6 while the remaining sites showed a gradual increase in pH towards the bottom of the catchment (Figure 7.1). Crystal Creek has a median pH of 5.7.

Figure 7.1: Summary statistics for pH at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



The pH of all sites showed considerable seasonal variation through the year. Spot sampling of pH indicated slightly higher levels in the first half of the year, followed by a decrease with increased flow rates in the second half of the year. For all sites the lowest values were recorded during the winter storm and the highest at the peak of summer (Figure 7.2).

Figure 7:2: Spot sampling changes for pH at several sites in Warra Creek and the base of Crystal Creek during 2001.



7.3.2. Electrical conductivity

Electrical conductivity reflects levels of total dissolved solids and major ions in the water. Conductivity of all sampling sites was very low and relatively stable throughout the year, except for Crystal Creek where a substantial range of conductivity values occurred (Figure 7.3). Highest maximum values were recorded in late summer, while minimum values were recorded during the winter storm (Figure 7.4).

Figure 7.3: Summary statistics for electrical conductivity at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.

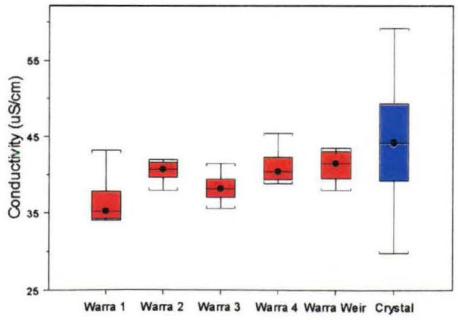
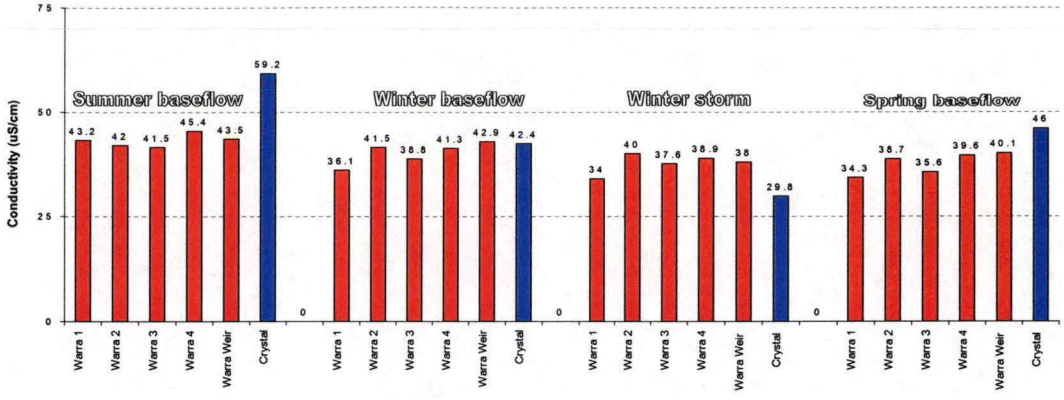


Figure 7.4: Spot sampling changes for electrical conductivity at several sites in Warra Creek and the base of Crystal Creek during 2001.



7.3.3 Turbidity

Turbidity of Warra Creek produced a large range of values with medians of around 1.5 NTU for most sites. Site 2 has the highest median value of 2.1 NTU, while Crystal Creek had the lowest median levels of 0.5 NTU. The range of values was largely due to elevated levels during the winter storm sampling period, where Site 2 reached 3.1 NTU and Crystal Creek reached 2.5 NTU (Figure 7.5). These higher turbidity values during rainfall events are caused by runoff water carrying suspended materials from diffuse sources from across the catchment.

When median values per contributing hectare are plotted for each location, it is evident that the upper tributaries of Warra Creek supply the majority of turbidity, especially water flowing out of site 2. (Figure 7.6

Figure 7.5: Summary statistics for turbidity at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.

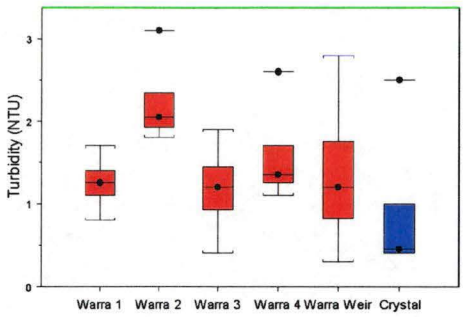
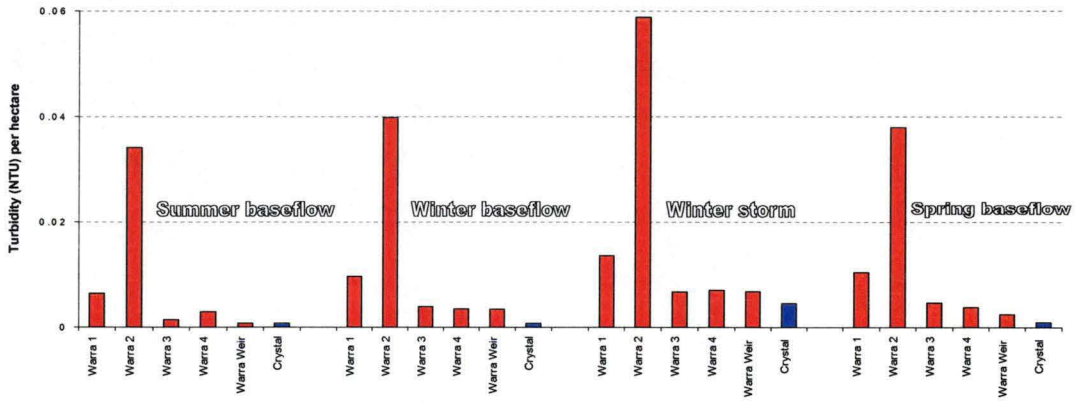


Figure 7.6: Median values per hectare of contributing catchment above each site for turbidity in Warra Creek and the base of Crystal Creek during 2001.



7.3.4 Apparent colour

Apparent colour values are very high in the top of Warra Creek catchment, with site 2 having median values of 279 (CU) and a maximum of 337 (CU) during the winter storm event. Site 1 is also moderately high with a median value of 91 (CU) (Figure 7.7). A decrease in colour towards the lower reaches of Warra Creek occurs as increased water from the remainder of the catchment dilutes the high amounts from site 2.

Crystal Creek was found to have relatively low colour readings with all values for baseflow periods below 20 CU. The median result is still only 15 CU despite the high reading of 89 CU during the highflow sampling period. Highflow sampling results for all Warra Creek sites were at least double the values found during baseflow periods, while Crystal Creek recording a four-fold increase.

Figure 7.7: Summary statistics for apparent colour at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.

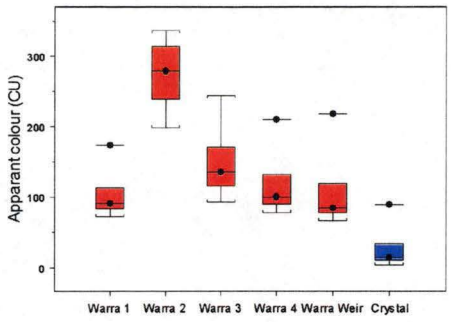
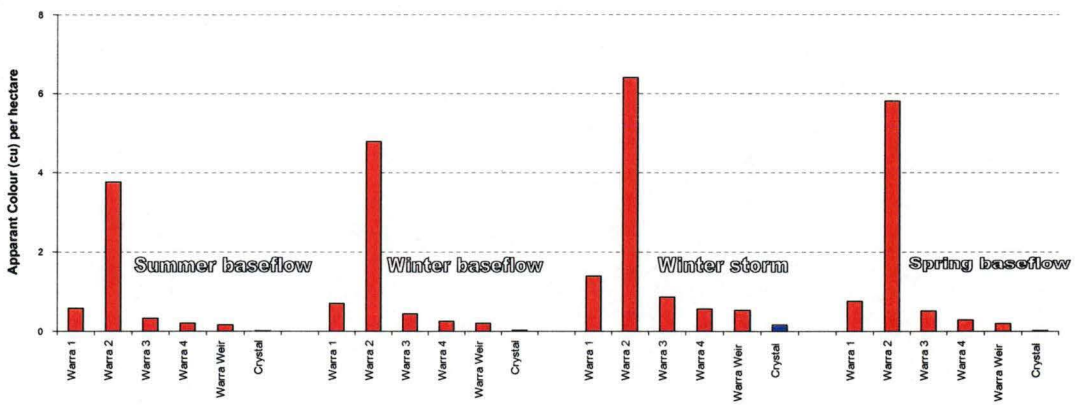


Figure 7.8 highlights site 2 as contributing the majority of colour to Warra Creek, with increased levels found at all sites during the winter storm event and at the higher spring baseflow periods.

Figure 7.8: Median values per hectare of contributing catchment above each site for apparent colour in Warra Creek and the base of Crystal Creek during 2001.



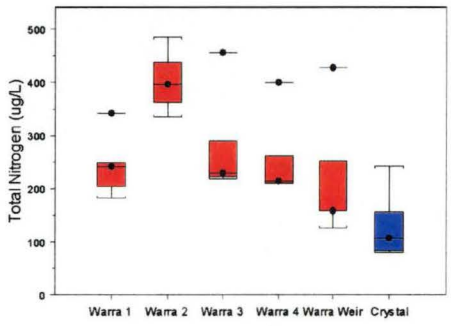
7.4 Nutrients

7.4.1 Total nitrogen

Total nitrogen concentrations follow a very similar pattern to apparent colour levels with site 2 containing the highest, followed by site 1 and then a gradual decrease in concentration towards the lower reaches of Warra Creek. Crystal Creek again has the lowest readings (Figure 7.9).

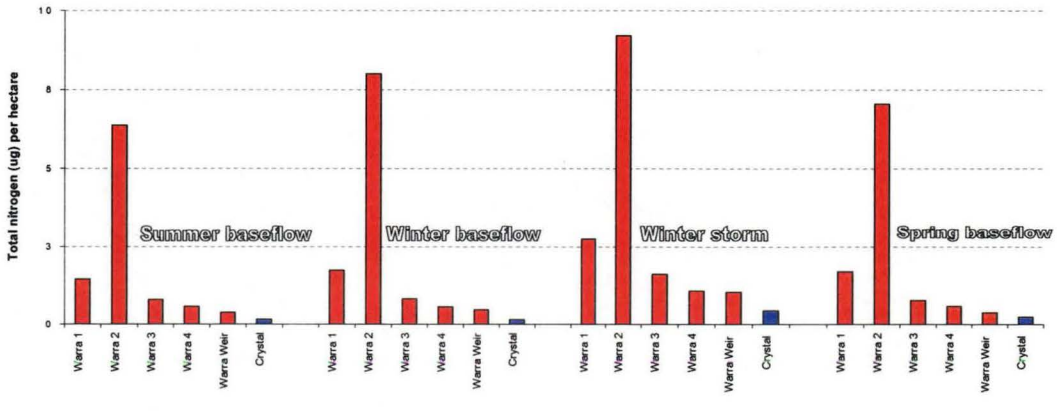
Median nitrogen concentrations are quite high across the locations, with large maximums due to increased flow rates during the winter storm. ANZECC (1996) suggests that for upland rivers, concentrations of 340 micrograms per litre could be used as a trigger level for assessing risk of adverse effects due to nutrients in natural systems. Site 2 is consistently over this level, with a median of 396 micrograms per litre and a maximum during the storm of 485 micrograms per litre. During the winter storm all of the sites in Warra Creek exceeded this guideline, while Crystal Creek reached 242 micrograms per litre.

Figure 7.9: Summary statistics for total nitrogen concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Site 2 accounted for the majority of the total nitrogen concentrations in Warra Creek. Although increased levels were found at all sites during the winter storm event (Figure 7.10).

Figure 7.10: Median values per hectare of contributing catchment above each site for total nitrogen in Warra Creek and the base of Crystal Creek during 2001.



7.4.2 Ammonium

Ammonia concentrations are very low in both catchments with all median levels below 46 micrograms per litre (Figure 7.11). Sites 1, 2 and 4 show a consistently small range of concentrations, while site 3, Warra Creek weir site and Crystal Creek have large concentration changes throughout the sampling period. This variation is due to changes in the breakdown rates of nitrogenous matter as a result of seasonal effects on vegetation and changes in animal excrement rates.

Figure 7.11: Summary statistics for ammonia concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.

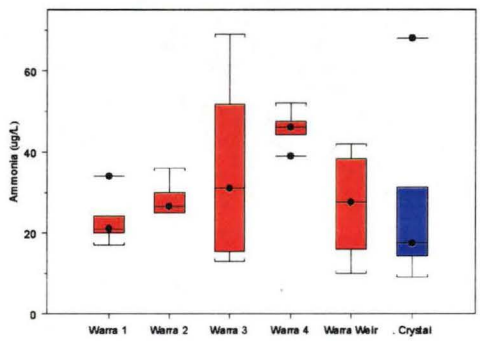
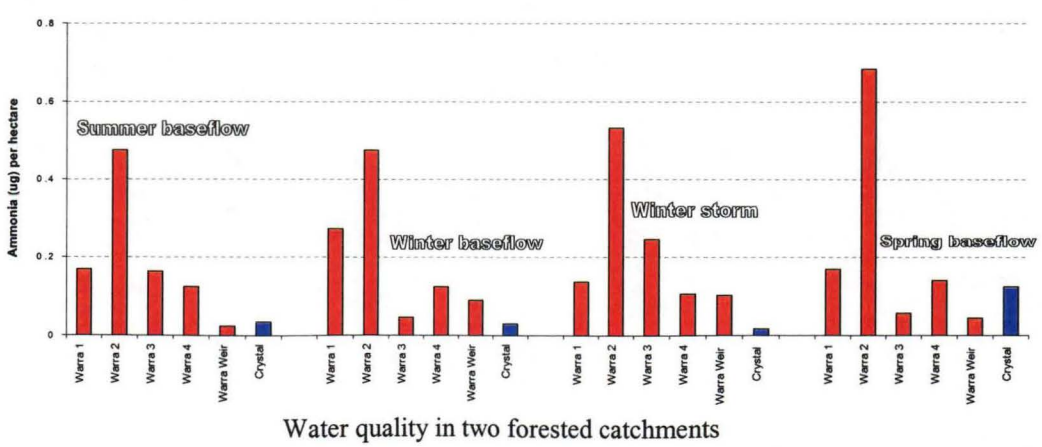


Figure 7.12 indicates that, per hectare, Site 2 contributes the highest median ammonium concentrations. However, other areas of the catchment are also contributing, resulting in a range of values across the locations. Crystal Creek has a consistent low amount of ammonia, with a large peak during the spring baseflow sampling period. This is likely to be due to increased litter fall, nutrient rich pollen, flower and insect parts which are deposited during late winter early autumn and are beginning to decompose (Swain et al. 1993).

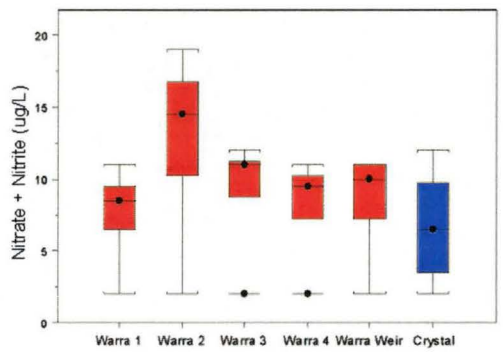
Figure 7.12: Median values per hectare of contributing catchment above each site for ammonia in Warra Creek and the base of Crystal Creek during 2001.



7.4.3 Nitrate and nitrite

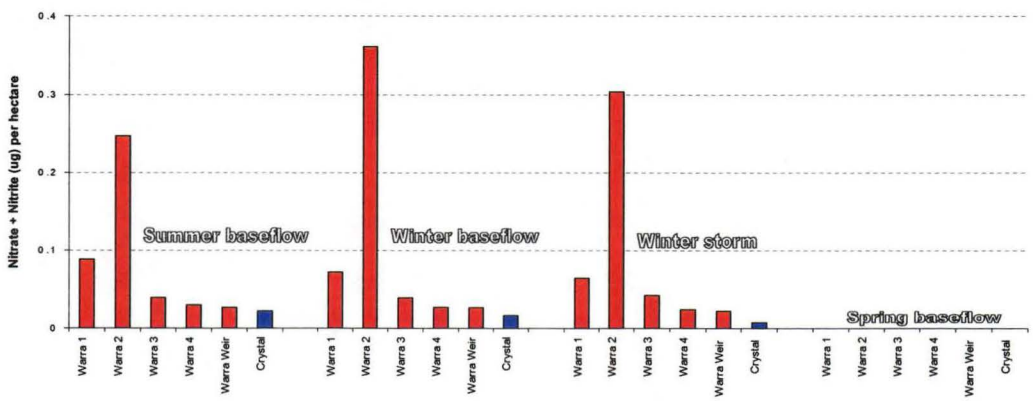
Nitrate plus nitrite levels are highest during winter baseflows, when groundwater discharge is at its highest level. Median concentrations were around 10 micrograms per litre, which is extremely low (Figure 7.13). Minimum levels occurred during spring baseflow sampling periods when concentrations were below detectable limits. Low spring levels are due to the flushing out of groundwater sources during high rainfall in winter and spring.

Figure 7.13: Summary statistics for nitrate and nitrite concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Site 2 is highlighted as containing the highest levels of oxidised nitrogen, followed by site 1. A decrease in median concentrations occurs with increasing flow further downstream (Figure 7.14). Crystal Creek has its highest levels in summer followed by a gradual decrease throughout the year as the supply of decomposing plant and animal debris is exhausted.

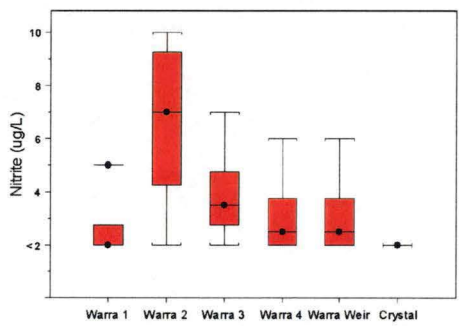
Figure 7.14: Median values per hectare of contributing catchment above each site for nitrate and nitrite in Warra Creek and the base of Crystal Creek during 2001.



7.4.4 Nitrite

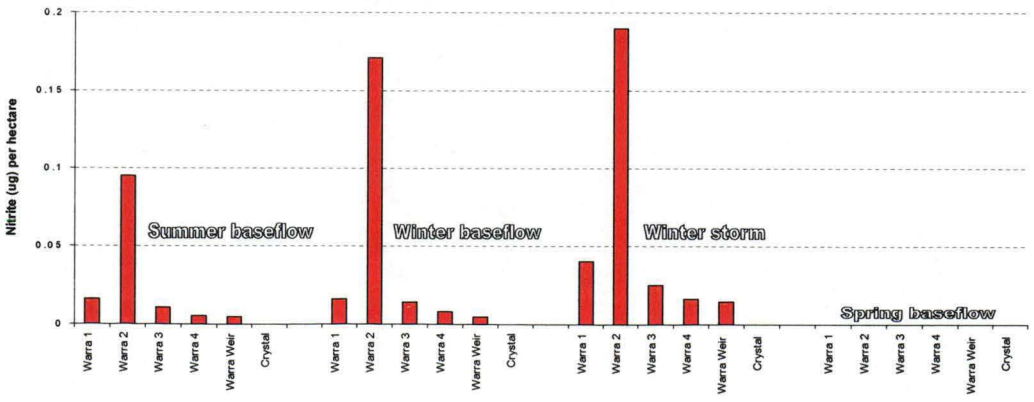
Nitrite concentrations in freshwaters are usually very low, and seldom exceed 10 micrograms per litre (Chapman 1996). The median concentrations for all locations are well below this level, although site 2 does reach a maximum concentration of 10 micrograms per litre during the winter storm sampling period (Figure 7.15). A large range of nitrite concentrations occurs for each site due to a general trend of increasing nitrite levels with flow, culminating with maximums during the winter storm event. Crystal Creek nitrite levels were extremely low and did not exceed detectable limits.

Figure 7.15: Summary statistics for nitrite concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



A general trend exists for increasing median nitrite concentrations through the season and decreasing levels from the top of the catchment to the bottom. Site 2 again stands out as being the major contributor of nitrite into Warra Creek. Spring samples were below detectable limits, possibly due to an exhaustion of nitrite caused by the large runoff effects over the winter months.

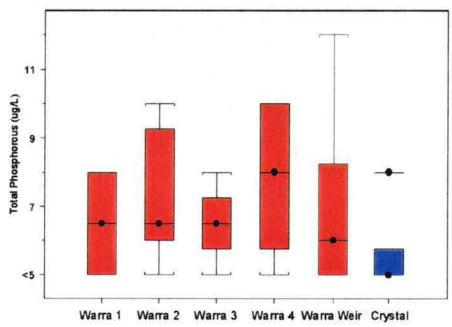
Figure 7.16: Median values per hectare of contributing catchment above each site for nitrite in Warra Creek and the base of Crystal Creek during 2001.



7.4.5 Total phosphorus

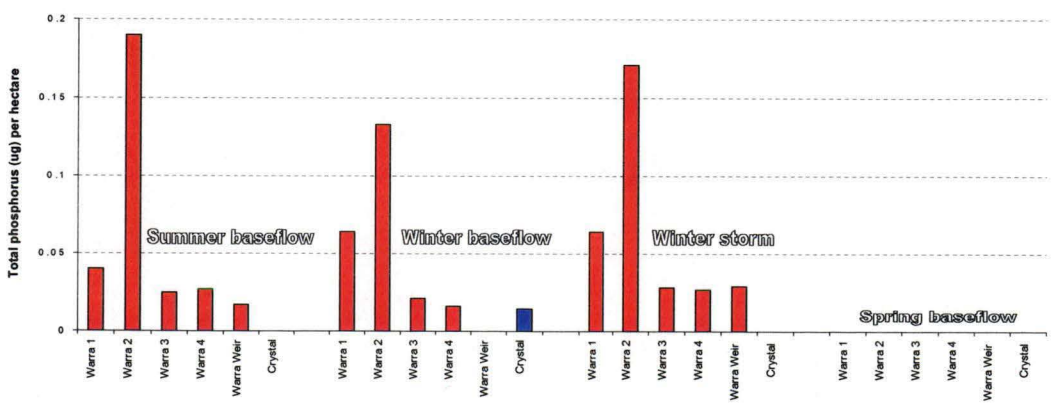
Total phosphorus accounts for both dissolved and particulate forms depending on environmental conditions and biological processes. Concentrations were extremely low in all locations ranging between the detectable level of 5 micrograms per litre up to a maximum of 12 micrograms per litre, during the winter storm (Figure 7.17). Median levels were relatively consistent across Warra Creek catchment. Only one sample from Crystal Creek contained phosphorus above detectable limits, which was collected during the winter baseflow event.

Figure 7.17: Summary statistics for total phosphorus concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



No seasonal trend exists in median phosphorus concentrations (Figure 7.18). The top of the catchment (particularly site 2) contains the highest concentration per hectare of total phosphorus.

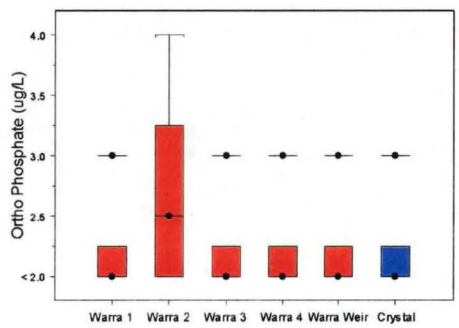
Figure 7.18: Median values per hectare of contributing catchment above each site for total phosphorus in Warra Creek and the base of Crystal Creek during 2001.



7.4.6 Ortho-phosphate

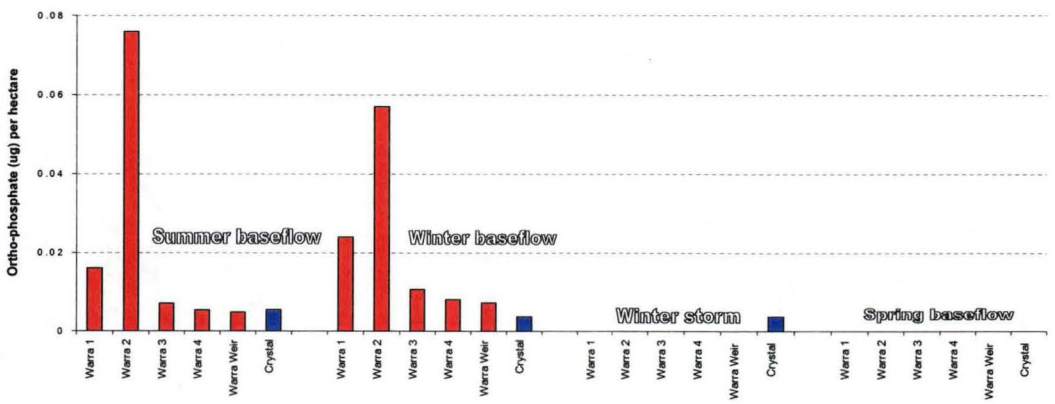
Ortho-phosphate is produced from the decomposition of organic material. Levels were extremely low and were only detected in the early half of the year during baseflow periods (Figure 7.19). Detectable limits were 2 micrograms per litre. Site 2 produced the highest concentrations, with a median of 2.5 micrograms per litre.

Figure 7.19: Summary statistics for ortho-phosphate concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Ortho phosphate levels appear to be highest during high baseflow periods and decrease in concentration the further they are diluted downstream.

Figure 7.20: Median values per hectare of contributing catchment above each site for ortho-phosphate in Warra Creek and the base of Crystal Creek during 2001.

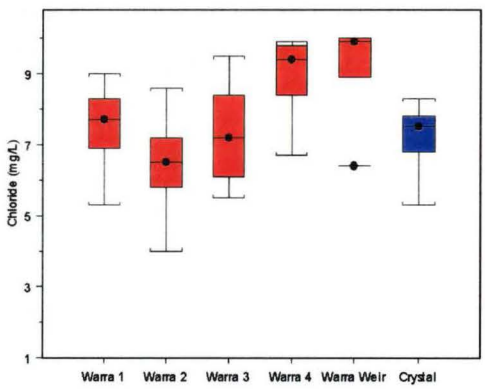


7.5 Major ions: anions

7.5.1 Chloride

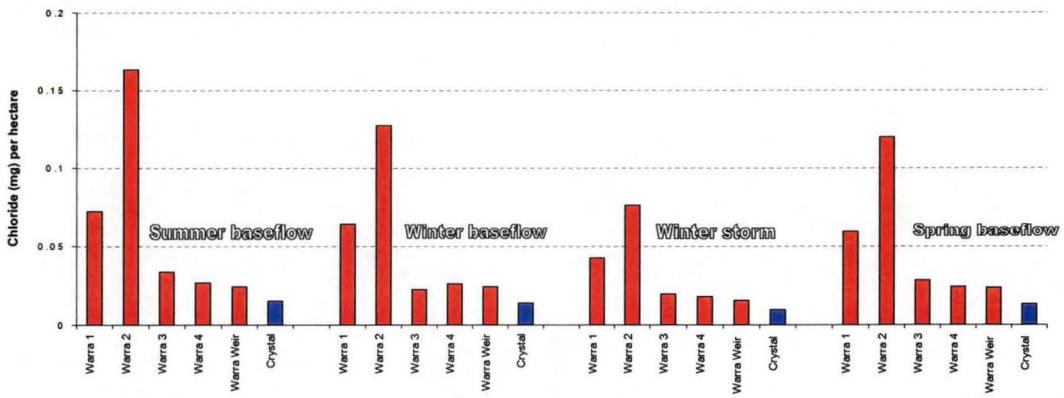
Chloride enters surface waters from the weathering of sedimentary rocks and the atmosphere, and hence concentrations can vary with flow. This may explain the large range of values found in the spot samples (Figure 7.21). Median levels were around 0.7 milligrams per litre across all locations except for site 4 and Warra Creek weir site that had raised concentration median of 9.4 and 9.9 milligrams per litre. This increase in concentration down the creek indicates a discharge of chloride from across the catchment.

Figure 7.21: Summary statistics for chloride concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Median chloride concentrations are highest during the lowest baseflow periods and lowest during the winter storm samples (Figure 7.22). This indicates that chloride is entering the creeks from the weathering of rocks. Sites 1 and 2 therefore should have the highest proportion of sedimentary rocks within their specific catchment boundaries. Geological mapping of the catchments confirms this result (Figure 5.5 and 5.6). Crystal Creek appears to also have sedimentary rocks within its catchment, leading to a continuous discharge of chloride throughout the year.

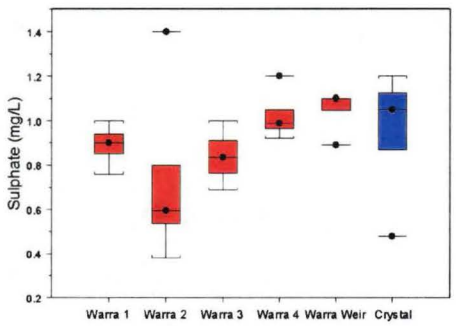
Figure 7.22: Median values per hectare of contributing catchment above each site for chloride in Warra Creek and the base of Crystal Creek during 2001.



7.5.2 Sulphate

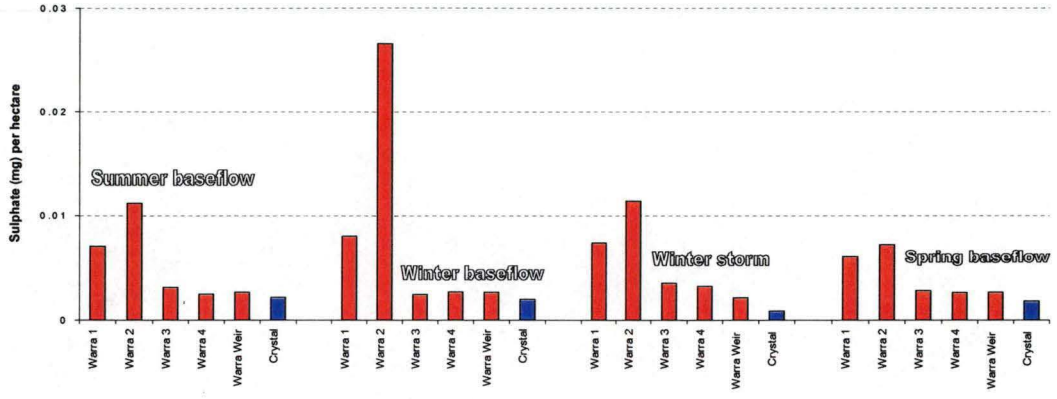
Sulphate also enters surface waters from the weathering of sedimentary rocks and the atmosphere. Concentrations of sulphate were relatively stable across the locations through the year, except for site 2 and Crystal Creek. Median levels were extremely low, ranging from 0.6 to 1.1 milligrams per litre. The base of both catchments contained the highest concentrations (Figure 7.23).

Figure 7.23: Summary statistics for sulphate concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Sulphate did not change through the seasons, except for site 2 and Crystal Creek (Figure 7.24). At these sites there is a distinct peak during winter baseflow, leading to a large change with flow in the winter storm and spring baseflow sampling periods, indicating that both sites are contributing sulphate to the baseflow waters in the catchments. Site 2 stands out as contributing the highest median concentration per hectare, although it is only notably higher during the winter baseflow periods.

Figure 7.24: Median values per hectare of contributing catchment above each site for sulphate in Warra Creek and the base of Crystal Creek during 2001.

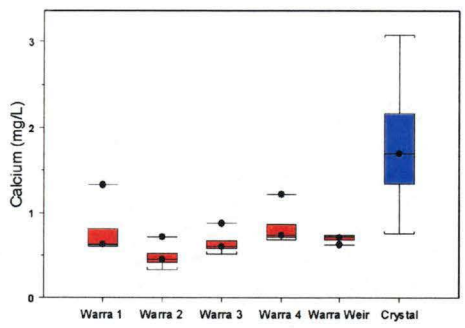


7.6 Major ions: cations

7.6.1 Calcium

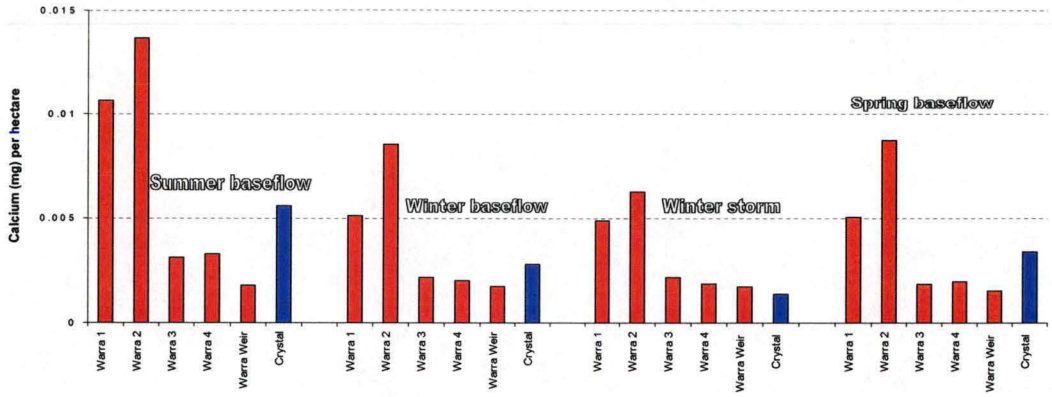
Total calcium in surface waters is derived from the weathering of rocks rich in calcium minerals, particularly areas rich in limestone and gypsum. Calcium concentrations are extremely low, with median levels less than 1.0 milligrams per litre in the surface waters of Warra Creek catchment (Figure 7.25). In comparison, calcium in Crystal Creek catchment had a large range of concentrations and a median rate of 1.7 milligrams per litre.

Figure 7.25: Summary statistics for total calcium concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Median calcium concentrations for all locations were highest in the summer baseflow periods and lowest during the winter storm sampling event. Increased rainfall therefore causes a decrease in the concentrations of these base cations. The top of Warra catchment contributes the majority of the calcium into the streamwater, indicating a point source for chemical weathering of the bedrock.

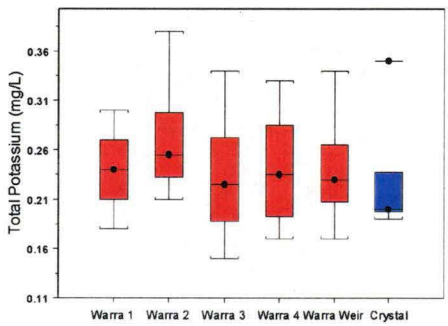
Figure 7.26: Median values per hectare of contributing catchment above each site for total calcium in Warra Creek and the base of Crystal Creek during 2001.



7.6.2 Potassium

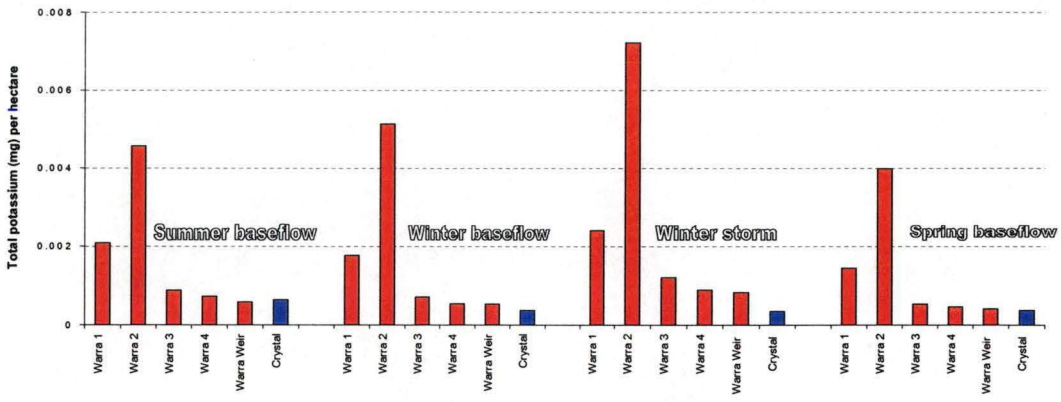
The median levels of about 0.25 milligrams per litre for total potassium were consistent across all sampling locations (Figure 7.27). A large range of values indicates a change in concentration with flow.

Figure 7.27: Summary statistics for total potassium concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Site 2 followed by site 1 contained the greatest proportion of potassium per hectare (Figure 7.28). There was a gradual increase in median concentration through the year culminating with the winter storm. A decrease from this highflow period followed with the spring baseflow sample.

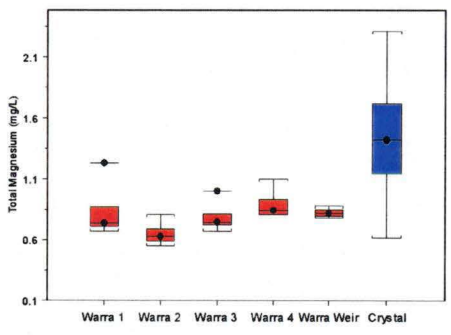
Figure 7.28: Median values per hectare of contributing catchment above each site for total potassium in Warra Creek and the base of Crystal Creek during 2001.



7.6.3 Magnesium

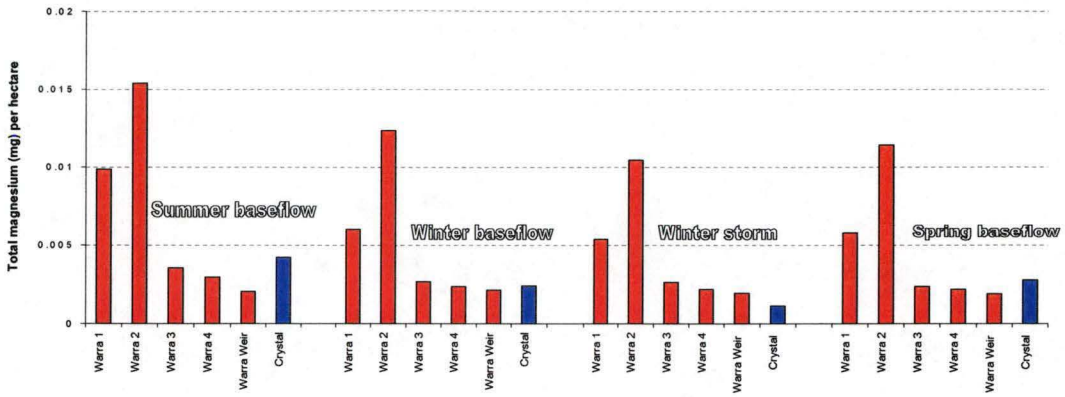
Total magnesium follows the pattern shown by total calcium, with very low medians and a low range of readings. Total magnesium concentration in Crystal Creek catchment stands out as being notably higher than Warra Creek catchment with a range of results across the year.

Figure 7.29: Summary statistics for total magnesium concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Highest levels occur during summer baseflow periods and lowest concentrations during the winter storm event (Figure 7.30). The top of Warra Creek catchment contributes the majority of magnesium to the surface waters of the creek. Levels at the base of Crystal Creek are higher than at the base of Warra Creek catchment.

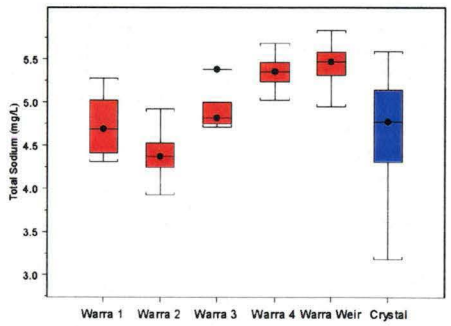
Figure 7.30: Median values per hectare of contributing catchment above each site for total magnesium in Warra Creek and the base of Crystal Creek during 2001.



7.6.4 Sodium

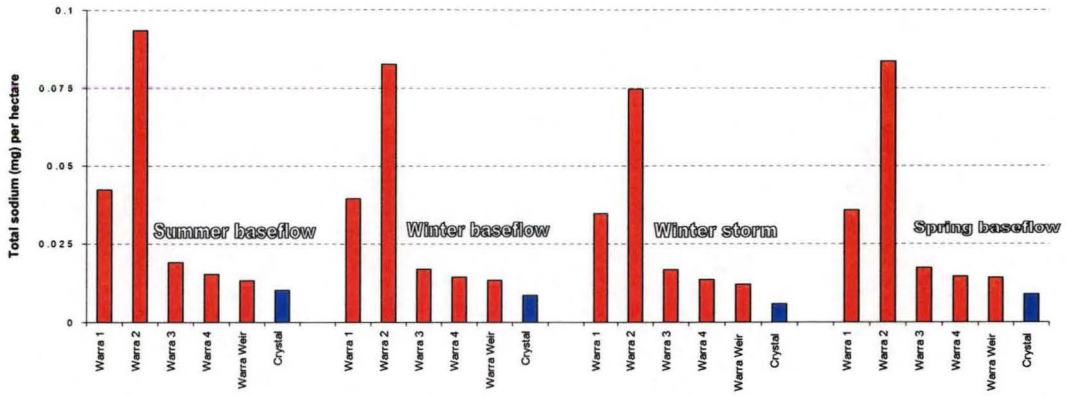
The median levels for total sodium were lowest at the top of Warra Creek catchment at site 2 with a concentration level of 4.38 milligrams per litre. Levels increased from this point downstream, culminating in a median level of 5.47 milligrams per litre at the Warra Creek weir site. Crystal Creek had a median concentration of 4.77 milligrams per litre and had the most variability in concentrations throughout the year (Figure 7.31).

Figure 7.31: Summary statistics for total sodium concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Total sodium levels were relatively steady throughout the year, with a slight decrease in concentrations occurring with the winter storm sample. Sites 2 and 1 had the highest readings per hectare for their relative areas of catchments (Figure 7.32)

Figure 7.32: Median values per hectare of contributing catchment above each site for total sodium in Warra Creek and the base of Crystal Creek during 2001.

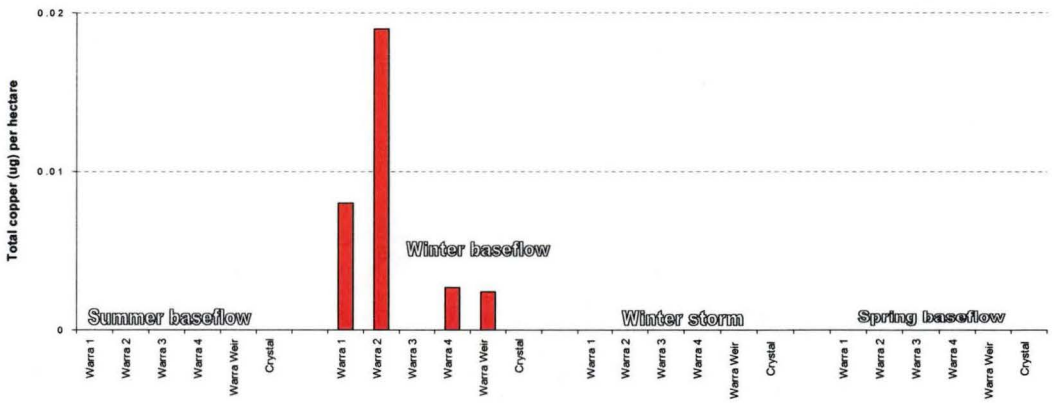


7.7 Other metals

7.7.1 Copper

Total copper concentration levels were not above the detectable limits during 2001 in all sites, except for during winter baseflow levels where levels reached the detectable limit of 1 milligram per litre.

Figure 7.33: Median values per hectare of contributing catchment above each site for total copper in Warra Creek and the base of Crystal Creek during 2001.

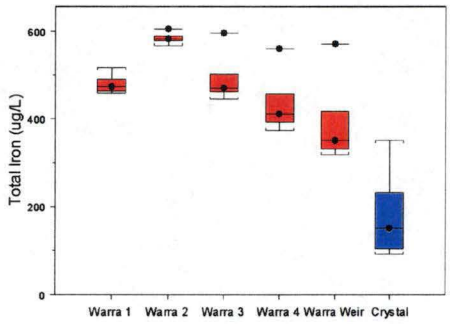


7.7.2 Iron

Total median iron concentrations were quite high in the Warra Creek catchment, with site 2 having a median level of 583.8 micrograms per litre (Figure 7.34). All other concentration in Warra Creek decreased at sites further downstream. Sites 1 and 2 had a very small range of values over the year, whereas other locations showed more

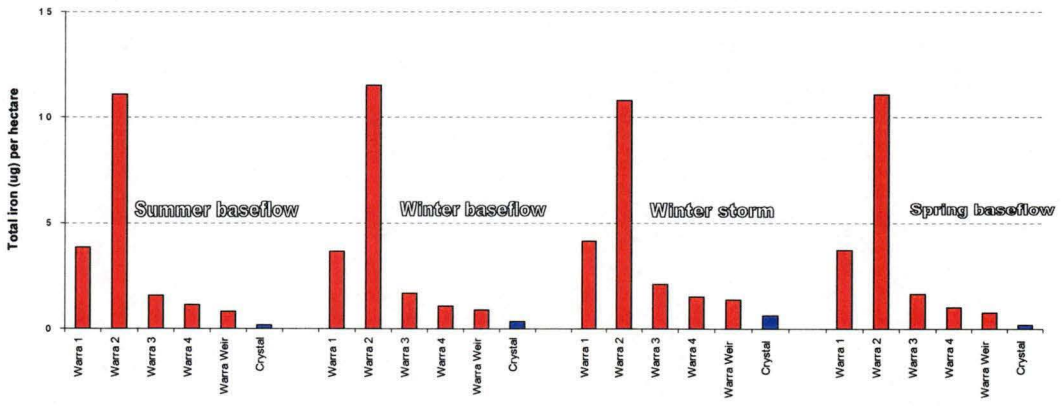
variability. Crystal Creek contained more than half the median concentration level than any location in Warra Creek catchment.

Figure 7.34: Summary statistics for total iron concentrations at several sites in Warra Creek and the base of Crystal Creek from spot samples collected during 2001.



Sites 1 and 2 are the point source for iron in the Warra Creek catchment (Figure 7.35). These sites displayed very little change with changes in flow, indicating a constant seepage into the streams regardless of water levels. The other sites are regulated by flow, with increases in concentrations occurring with increased times of flow.

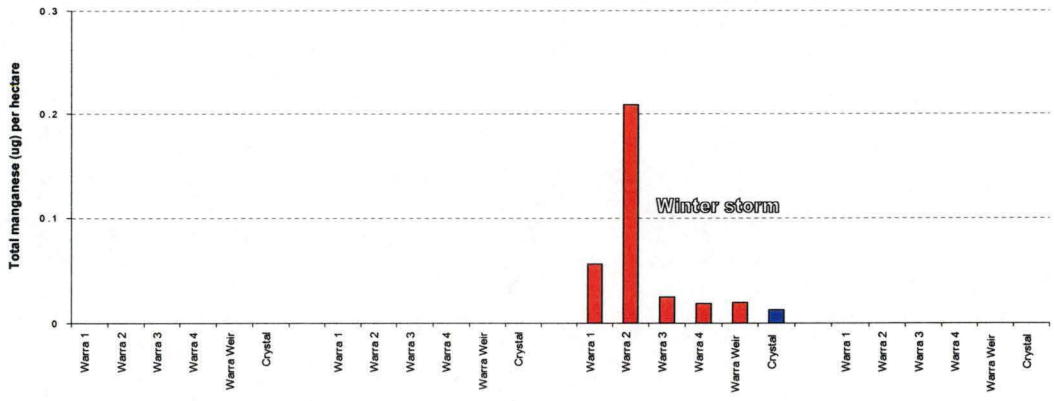
Figure 7.35: Median values per hectare of contributing catchment above each site for total iron in Warra Creek and the base of Crystal Creek during 2001.



7.7.3 Manganese

Total manganese concentration levels were not above detectable limits during 2001 in all sites, except during winter stormflow levels where levels reached the detectable limit of 2 micrograms per litre.

Figure 7.36: Median values per hectare of contributing catchment above each site for total manganese in Warra Creek and the base of Crystal Creek during 2001.



7.8 Summary

At the base of Warra and Crystal creek catchments all chemical and physical parameters were well below the guidelines set for assessing catchment health. However, apparent colour, total iron and nitrogen stand out as being moderately high in Warra Creek, particularly at site 2.

Parameters can be divided into three distinct types depending on their changes over the season. The three evident trends were increases in values with increased stage heights, no noticeable seasonal trends and decreases in values with decreased stage heights.

Several parameters displayed a distinct seasonal trend of increasing values with increasing stage heights, culminating in maximums during the winter storm event. These parameters were: apparent colour, total nitrogen, iron, turbidity, nitrite, ammonia and nitrate and nitrite. For all parameters, site 2 had the highest values, followed by either site 1 or site 3 and then a gradual decrease at sites further downstream. Crystal Creek catchment always had a lower median value than the Warra Creek weir site. Ammonia was the exception with a general increase in concentrations with a decrease in altitude.

Site 2 had the highest median values for the above parameters over the year. When these were assessed per hectare of contributing catchment above each site, a

significant finding became evident. The areas above site 2, closely followed by site 1, were the major sources of colour and associated nutrients in Warra Creek catchment.

Some of the parameters displayed no noticeable seasonal or catchment trends including: electrical conductivity, total phosphorus, total potassium, total copper and total manganese. Copper and manganese concentrations were so low they could often not be detected. The other parameters showed quite even levels through the year and across the Warra Creek catchment sites. Crystal Creek catchment had moderately lower median levels than those found at the Warra Creek weir site, except for conductivity where Crystal Creek exhibited the highest median value.

The remaining parameters display a negative relationship with flow. Ortho-phosphate, pH, chloride, sulphate, calcium, magnesium and sodium all displayed a seasonal trend of peaks during summer baseflows and troughs during winter storm events. Levels of these parameters in Warra Creek catchment were the opposite of parameters that peak during winter storms, (i.e., levels were lowest in site 2, followed by site 1 and 3 leading to a peaks at the Warra Creek weir site. Crystal Creek had higher levels for magnesium, calcium, sulphate and pH than Warra Creek.

Ionic proportions in Warra catchment were $Na^+ > Mg^{2+} > Ca^{2+}$, while in Crystal they were $Na^+ > Ca^{2+} > Mg^{2+}$, except during the winter storm when they were also $Na^+ > Mg^{2+} > Ca^{2+}$. Medium measurements of sodium were similar at both Warra and Crystal creeks. However, in Crystal Creek, calcium values were more than double Warra Creek and magnesium almost double. This indicates that the composition of water in Warra Creek catchment is very similar to dilute seawater (type one waters). While in Crystal Creek catchment the waters show some aspects of geochemical influence (type three waters), except during high rainfall events when new water changes the baseflow compositions to one reflecting dilute seawater.

The results presented in this chapter provide a number of insights that help to address the aim of this study, which was to investigate the source of colour and apparent nutrient enrichment in Warra Creek catchment.

Chapter 8: Storm water sampling results

8.1 Introduction

Muscutt et al. (1990) demonstrated that rainfall induces changes in the predominant water pathways that affect streams, resulting in a change to the supply of ions to surface waters. This ionic change in surface waters during rainfall events has a significant effect on water quality. A more intensive sampling system designed to analyse stream parameter levels through particular storm events was therefore conducted. Both Warra and Crystal creeks were analysed during autumn and winter storm events through the use of two Trade 12M Gamet automatic liquid sampling systems. Data were analysed through line graphs and Pearson product correlations.

8.2 Storm water heights

Two storms were analysed, one from 11/4/2001 to 13/4/2001 and the other towards the end of winter from 16/9/2001 to 18/9/2001. Water samples were taken every two hours during the autumn storm and every hour during the winter storm. Turbidity, pH and conductivity were measured on each collected sample (Figures 8.1 and 8.3). A subset of ten samples from each storm and each creek were analysed for the full range of chemical parameters (Figures 9.2 and 8.4).

The autumn storm although not the first storm of the year, was the largest storm in autumn and generated a greater stream height than any of the proceeding storms (Appendices 8,9,10,11 and Figures 6.1 and 6.2). This storm caused Warra Creek to rise 450 millimetres in 21 hours, reaching a peak at 700 millimetres, and then slowly declined over the next 24 hours. The winter storm occurred at the end of winter after a period of low rainfall (Appendices 12,13,14 and 15). Warra Creek rose rapidly, increasing 500 millimetre in just 11 hours, reaching a peak of 657 millimetres, then slowly declined over the next 36 hours.

Figure 8.1: Autumn hydrograph at Warra Creek weir (over 2 days) displaying points where water samples were taken for physical analysis in Warra and Crystal creeks.

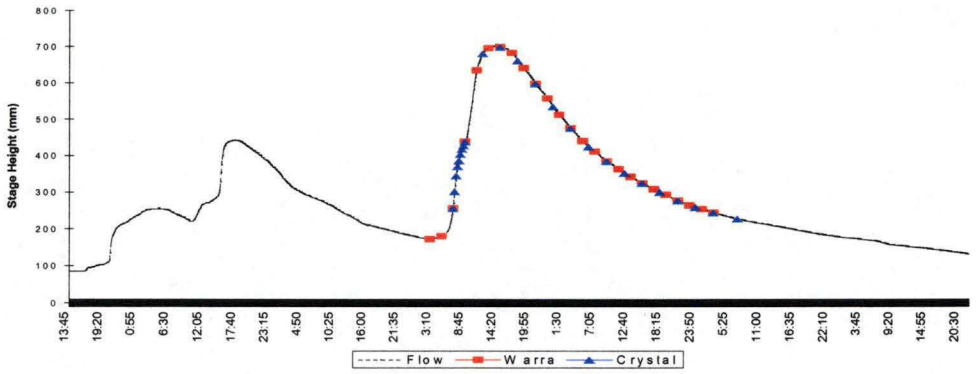


Figure 8.2: Autumn hydrograph at Warra Creek weir (over 2 days) displaying points where water samples were taken for chemical analysis in Warra and Crystal creeks.

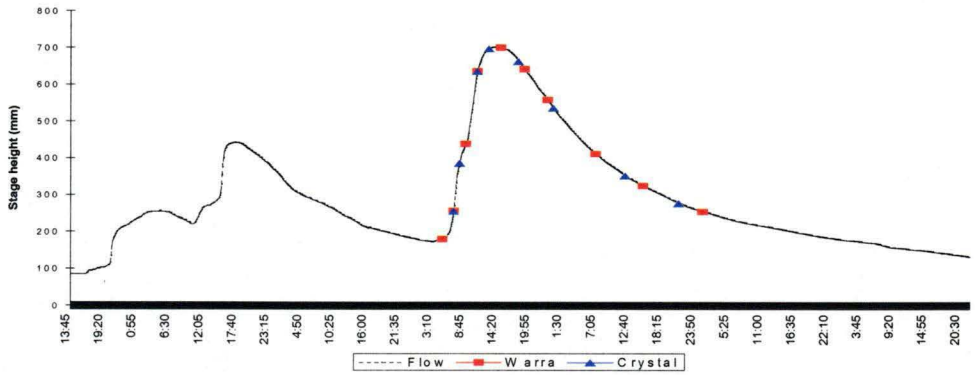


Figure 8.3: Winter hydrograph at Warra Creek weir (over 2 days) displaying points where water samples were taken for physical analysis in Warra and Crystal creeks.

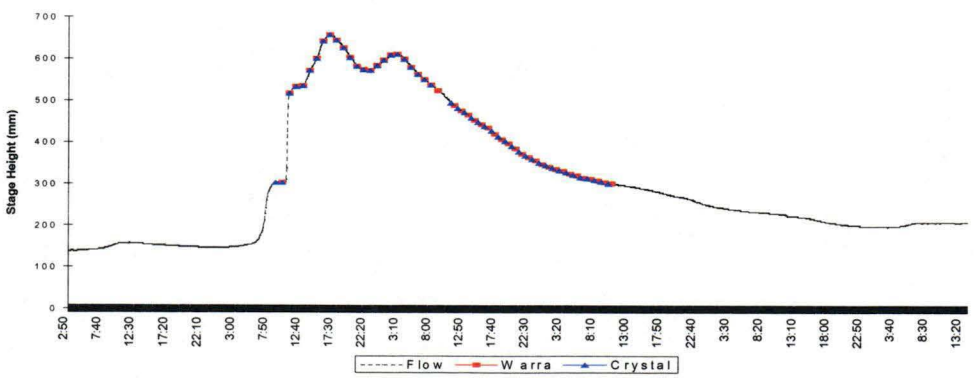
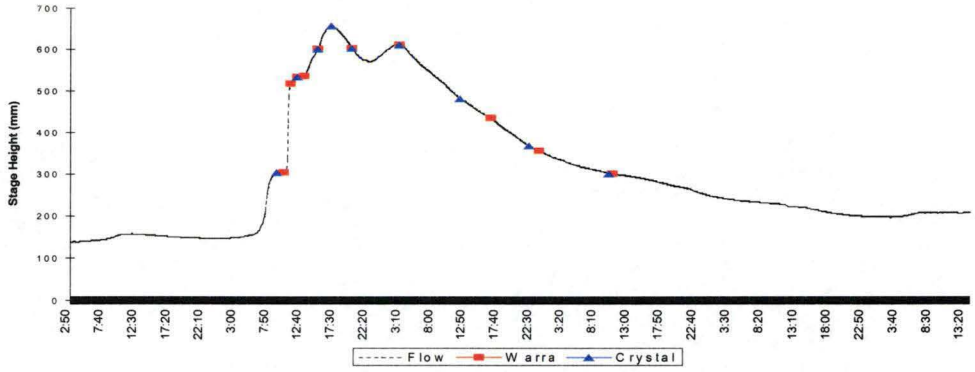


Figure 8.4: Winter hydrograph at Warra Creek weir (over 2 days) displaying points where water samples were taken for chemical analysis in Warra and Crystal creeks.



The streamwater levels of most ions analysed for both Warra and Crystal creeks in both storms increased during the rainfall event, but the timing of these increases varied between storms and according to the initiation of flows that control each particular parameter. The majority of the parameters increased to reach peak levels during the rising limb of the hydrograph, and then fell according to the discharge of the stream water. However conductivity, pH and their associated ions either showed no correlation with stage height or were negatively associated with stage height.

Pearson product correlations between all parameters in each particular storm at Warra and Crystal creeks were produced. Any statistically significant correlations were tested by probability values and are reported as weak; low; moderate; strong; or very strong depending on their r^2 value. All correlations and probability values can be viewed in Appendices 8,9,10,12,13 and 14.

8.3 Physical parameters

Turbidity in both Warra and Crystal creeks during both storm events reached a peak prior to the peak in stream height. During the autumn storm, Crystal Creek maintained these elevated turbidity levels from the onset of the storm through to the beginning of flow decline. There was therefore no correlation between turbidity and stage height at Warra Creek for either storm. However, at Crystal Creek the turbidity peak is slightly delayed causing a moderate correlation with stage height for both

storms (Figures 8.5 and 8.6). Maximum turbidity levels occurred during the winter storm with a peak of 12.2 (NTU) for Warra Creek and 14.1 (NTU) for Crystal Creek. Turbidity levels therefore exceeded the NHMRC guideline of ≤5 NTU and were greater than the 10 per cent change from seasonal mean as outlined by the ANZECC guidelines of 1996 (Warra Creek has 15 per cent change and Crystal Creek 21 per cent).

Electrical conductivity was not significantly affected by changes in stage height. However, a moderate correlation occurred between conductivity and stage height in Warra Creek during the autumn storm, and a moderate negative correlation occurred between conductivity and stage height in Crystal Creek during the winter storm (Figures 8.5 and 8.6). Conductivity at Warra reached a maximum level of 51.8 $\mu S/cm^{-1}$ during the autumn storm and a minimum level of 29.5 $\mu S/cm^{-1}$ at Crystal in the winter storm.

Figure 8.5: Autumn storm displaying physical parameter levels.

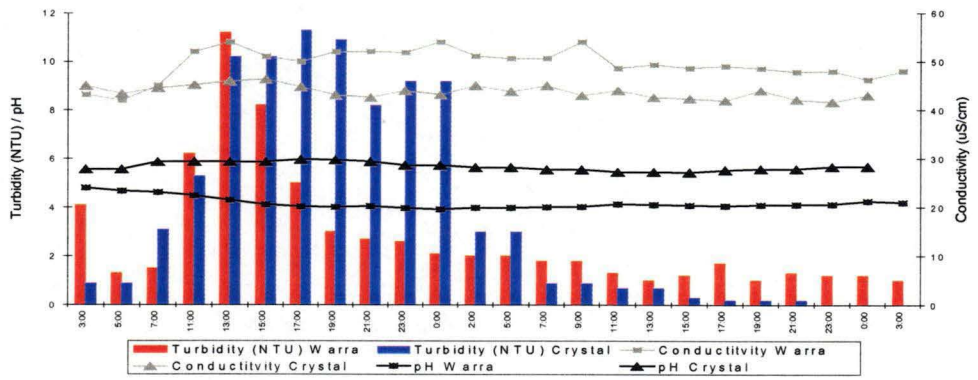
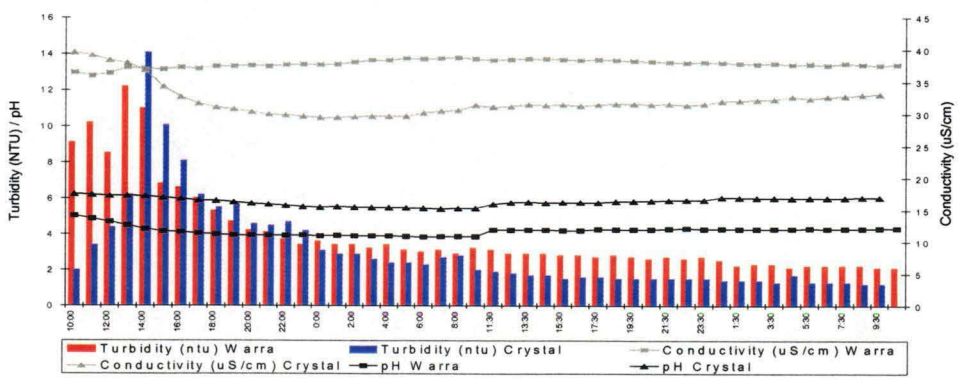


Figure 8.6: Winter storm displaying physical parameter levels.



pH was moderate to strongly negatively correlated with stage height in both autumn and winter storms at Warra Creek and in the winter storm at Crystal Creek. Warra Creek reached a minimum level of 3.9 (exceeding the < 5.0 guidelines as imposed by Kruger and Lubczenko, 1994) during the autumn storm, while Crystal Creek reached 5.4 in the winter storm Creek (Figures 8.5 and 8.6) .

In both Warra and Crystal creeks during the storms, apparent colour increases to a peak, but it was only correlated with stage height during the winter storm. Maximum apparent colour levels of 282 CU were recorded during the autumn storm in Warra Creek and 141 CU in Crystal Creek (Chesseman and Boey, 1992 consider levels of > 200 CU to be very high) (Figures 8.7 and 8.8).

Figure 8.7: Autumn storm displaying apparent colour levels.

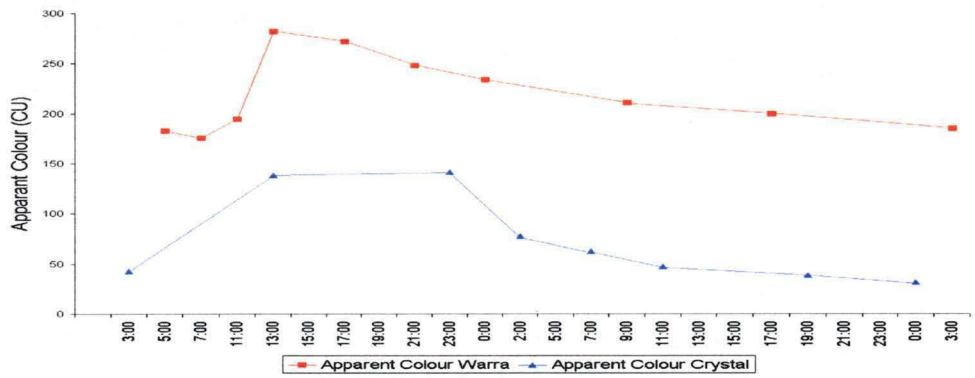
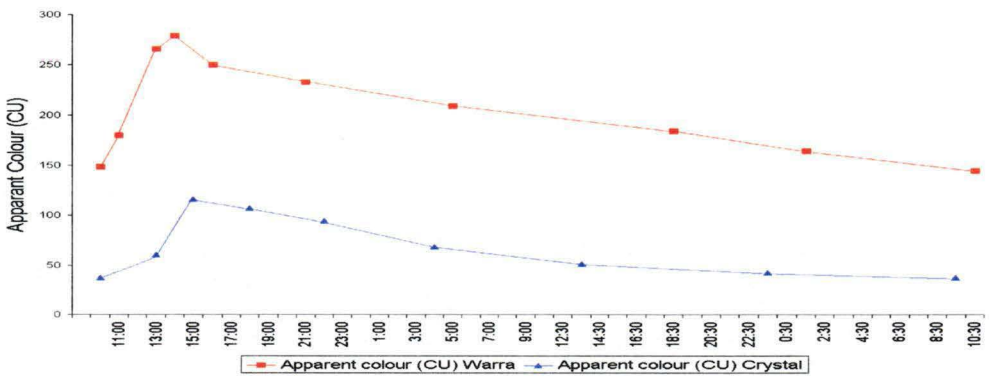


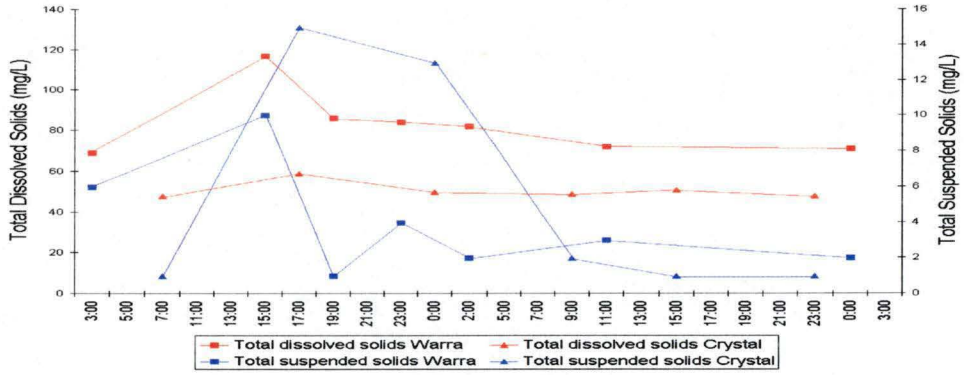
Figure 8.8: Winter storm displaying apparent colour levels.



Total dissolved and suspended solids were only analysed for the autumn storm. Concentration peaks of total dissolved and suspended solids occurred before stream peaks. However, in Crystal Creek stage height had little impact on the concentration levels of total dissolved solids (Figure 8.9). Total dissolved solids reached a

maximum of 117 milligrams per litre in Warra Creek and 59 milligrams per litre in Crystal Creek. Total suspended solids reached maximums of 10 milligrams per litre in Warra Creek and 15 milligrams per litre in Crystal Creek.

Figure 8.9: Autumn storm displaying total dissolved and suspended solids concentration.



8.4 Nutrients

Both total nitrogen and total phosphorus increased to a peak with storm events in both Warra and Crystal creeks (Figures 8.10 and 8.11). In Warra and Crystal creeks during the winter storm, concentration peaks occurred on the rising limb of the hydrograph. However, during the autumn storm at Crystal Creek, peaks in total nitrogen and total phosphorus coincided with stage heights, resulting in very strong correlations.

Total nitrogen reached a maximum of 712 micrograms per litre in Warra Creek during the winter storm and 451 micrograms per litre in Crystal Creek during the autumn storm (well above ANZECC, 1996 recommended guidelines). Total phosphorus reached maximum values during the winter storm event with 19 micrograms per litre recorded at Warra Creek and 15 micrograms per litre at Crystal Creek. Total nitrogen to phosphorus ratios were 37:1 in Warra Creek and 32:1 in Crystal Creek, this is 197 per cent and 152 per cent increase respectively, well above the recommended Tasmanian State of the Environment guidelines (Liston and Maher 1997).

Figure 8.10: Autumn storm displaying total nitrogen and total phosphorus concentrations.

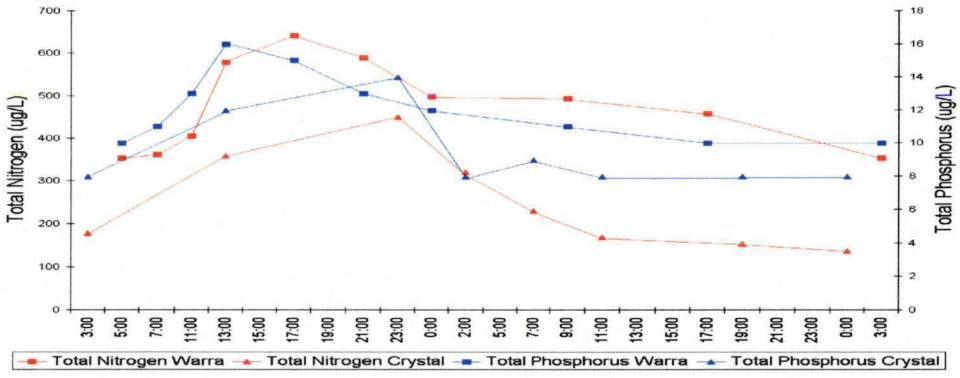
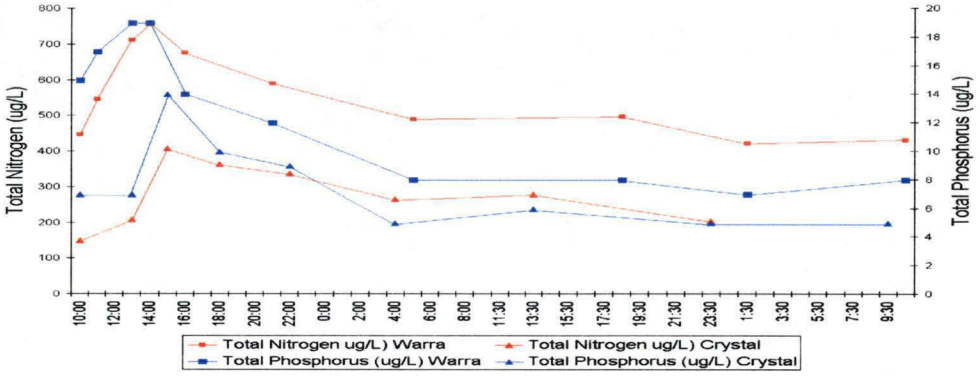


Figure 8.11: Winter storm displaying total nitrogen and total phosphorus concentrations.



Ammonia did not significantly change during the storm events, although a slight increase occurred with the onset of increased flow during both storms and in both Warra and Crystal creek. This delayed peak occurring after stream height peaks resulted in a very strong negative correlation between the winter storm stage height and ammonia at Crystal Creek (Figures 8.13 and 8.13). Maximum ammonia concentrations were 77 micrograms per litre in Warra Creek during the autumn storm and 60 micrograms per litre in Crystal Creek during the winter storm.

Ortho-phosphate levels was extremely low in both Warra and Crystal creeks for both storms and were generally not affected by stream height, except during the autumn storm in Warra Creek where levels increase by a third to peak before the storm flow peak (Figures 9.13 and 9.13). Maximum levels were 16 micrograms per litre in Warra Creek during the autumn storm and 2 micrograms per litre in Crystal Creek during both storms.

Figure 8.12: Autumn storm displaying ammonia and ortho-phosphate concentrations.

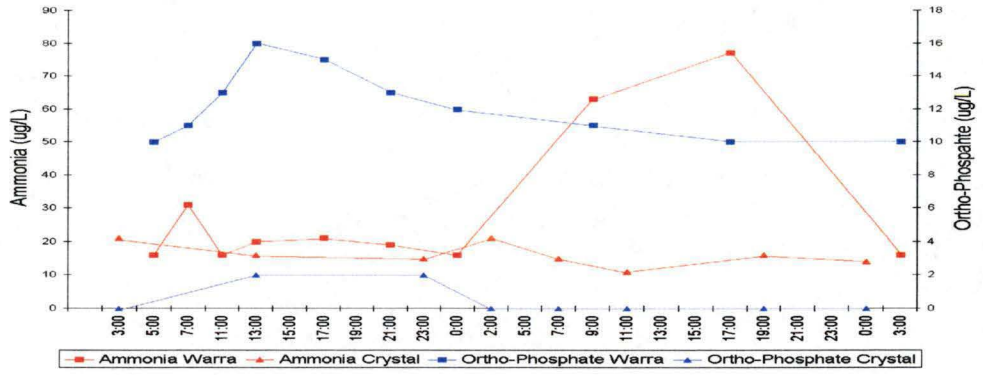
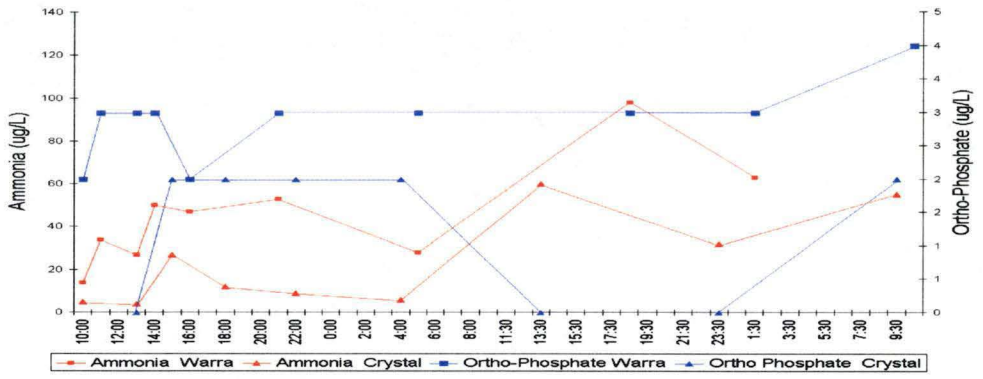


Figure 8.13: Winter storm displaying ammonia and ortho-phosphate concentrations.



Concentrations of nitrate + nitrite and nitrite in both creeks were extremely low, with levels in Warra Creek at least double that found in Crystal Creek. Concentrations did not significantly change during the autumn storm event. However, in both creeks slight increases in both parameters occurred prior to the winter storm peak, resulting in a strong correlation at Warra Creek between stage height and nitrate + nitrite and nitrite. (Figures 9.14 and 9.15). Nitrate + nitrite reached maximum levels of 12 micrograms per litre in Warra Creek during the autumn storm and 8 micrograms per litre in Crystal Creek during the winter storm. Nitrite reached maximum levels of 9 micrograms per litre in Warra Creek during the winter storm and 3 micrograms per litre in Crystal Creek during both storms.

Figure 8.14: Winter storm displaying nitrate + nitrite and nitrite concentrations.

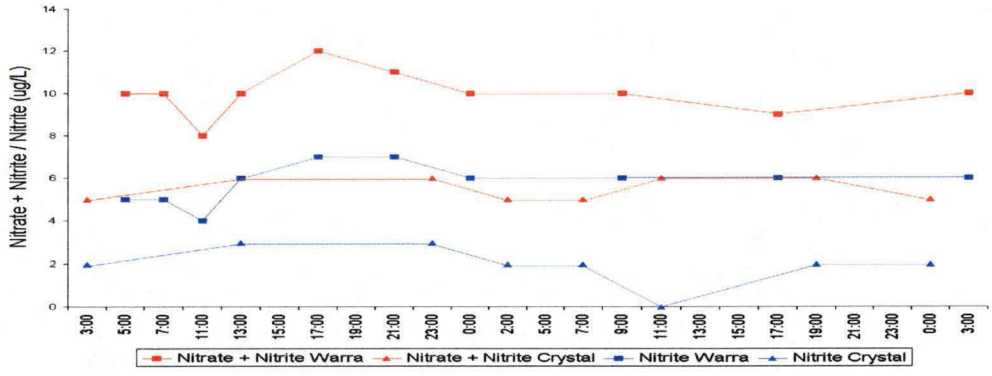
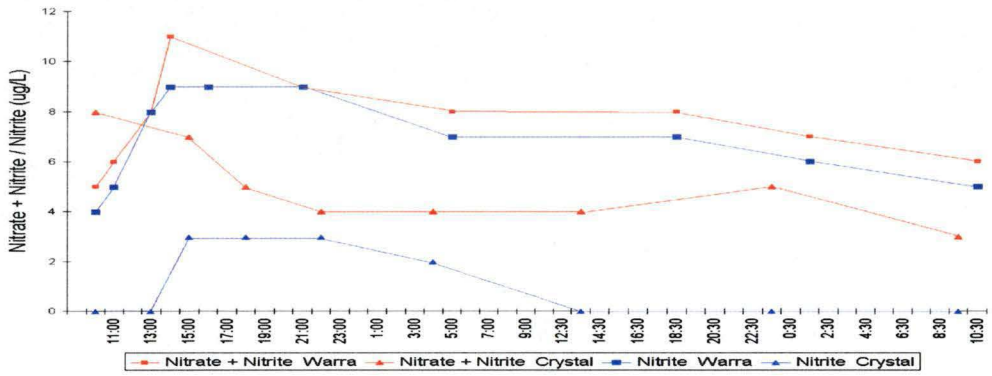


Figure 8.15: Winter storm displaying nitrate + nitrite and nitrite concentrations.



8.5 Major anions

In both Warra and Crystal creeks during both storms, increases in stream heights resulted in either no affect or a decrease in anion concentration. In Warra Creek this resulted in a very strong negative correlation between stage height and chloride for both storms (Figures 8.16 and 8.17). Minimum chloride concentrations were reached in the winter storm, Warra Creek recorded levels of 6.0 milligrams per litre and Crystal Creek 5.2 milligrams per litre.

Figure 8.16: Autumn storm displaying chloride and sulphate concentrations.

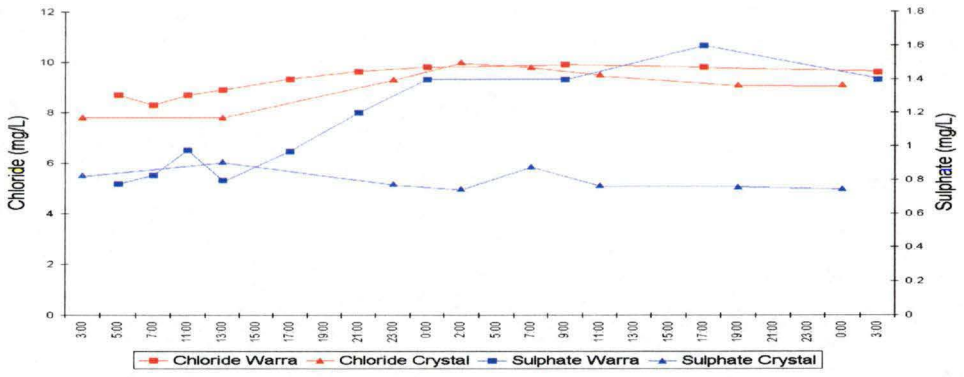
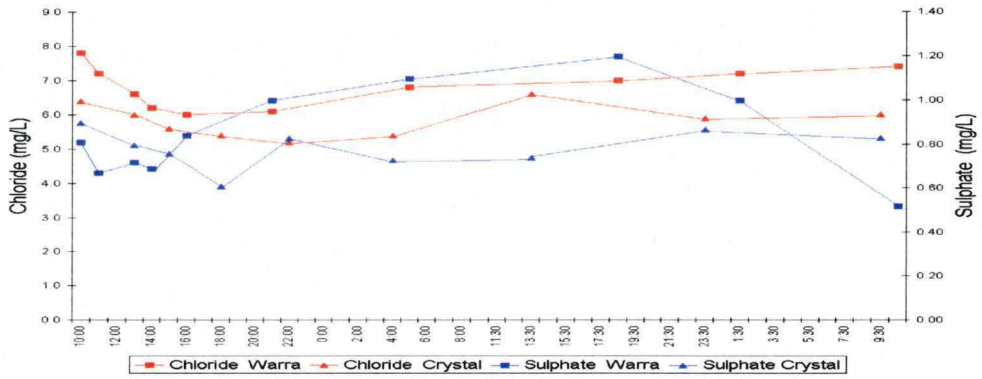


Figure 8.17: Winter storm displaying chloride and sulphate concentrations.



Sulphate in Warra Creek reached a maximum level of 1.6 milligrams per litre in the autumn storm, while Crystal Creek reached 0.91 milligrams per litre. However, sulphate concentrations in Crystal Creek decreased during the winter storm, reaching a minimum of 0.61mg/L.

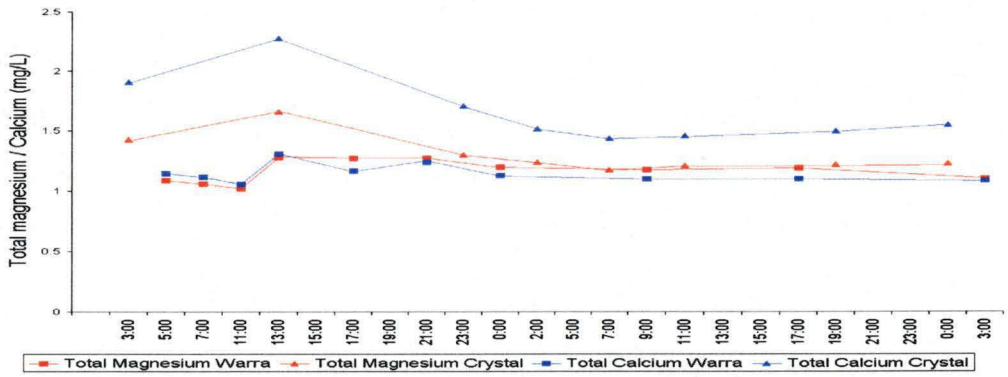
8.6 Major cations

The increases in streamflow caused by the two sampled storms had little impact on major cations, resulting in either no effect, or slight rises before storm peaks. All major cation concentrations were very low. However, unlike other parameters measured, rates of calcium, magnesium and potassium (autumn storm only) were higher in Crystal than Warra Creek (Figures 8.18, 8.19, 8.20 and 8.21).

Calcium reached its maximum in the autumn storm with 1.24 milligrams per litre recorded in Warra Creek and 1.71 milligrams per litre in Crystal Creek. Crystal

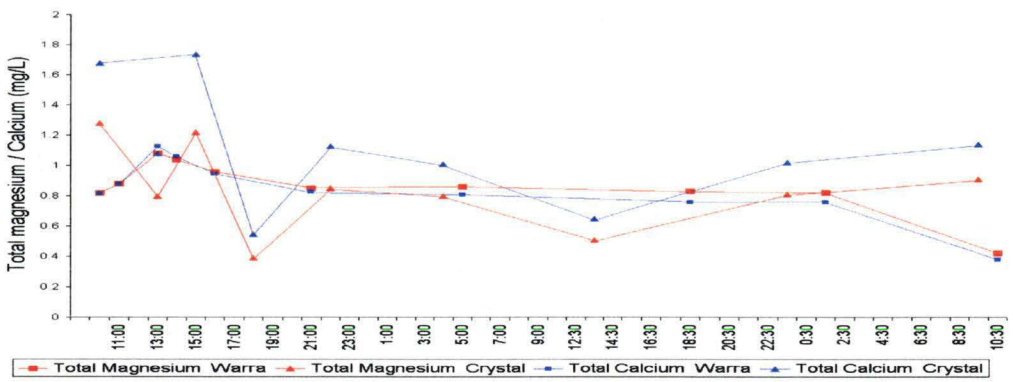
Creek reached a minimum concentration of 0.55 milligrams per litre during the winter storm.

Figure 8.18: Autumn storm displaying total magnesium and total calcium concentrations.



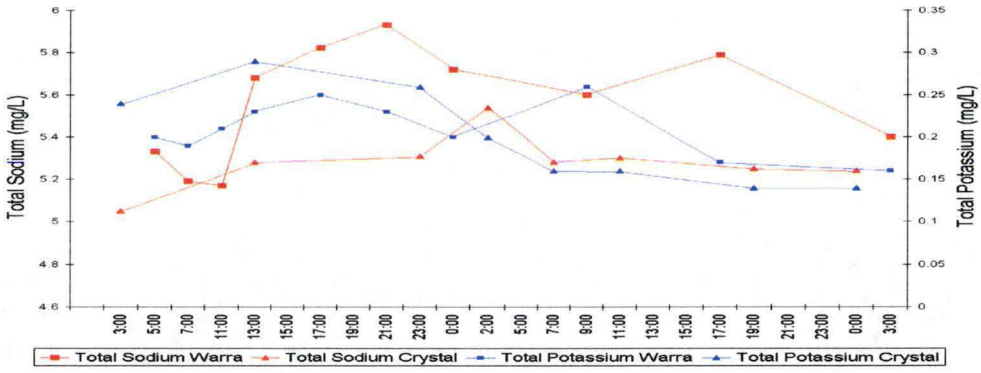
Magnesium also reached its maximum in the autumn storm with 1.27 milligrams per litre recorded in Warra Creek and 1.66 milligrams per litre in Crystal Creek. Magnesium concentrations in Crystal Creek reached a minimum concentration of 0.39 milligrams per litre during the winter storm.

Figure 8.19: Winter storm displaying total magnesium and total calcium concentrations.



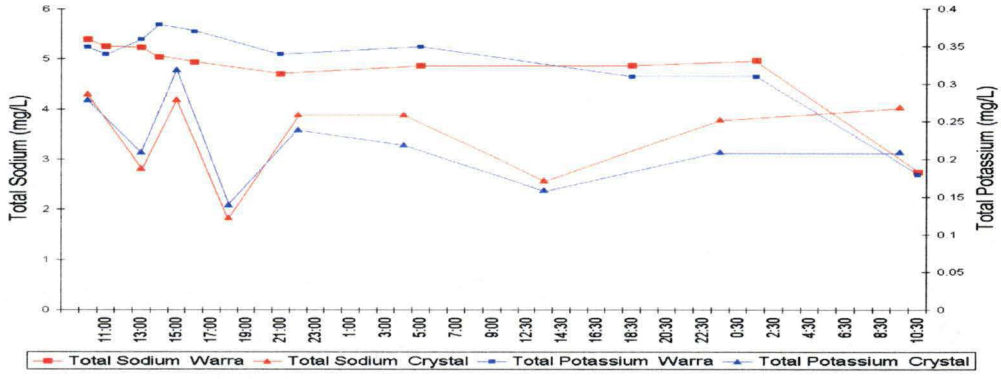
Potassium concentrations reached a maximum in Warra Creek during the winter storm with 0.38 milligrams per litre recorded in Warra Creek. Potassium concentrations in Crystal Creek reached a maximum of 0.29 milligrams per litre (autumn) and a minimum of 0.14 milligrams per litre during the winter storm.

Figure 8.20: Autumn storm displaying total potassium and total sodium concentrations.



Sodium also reached its maximum concentration during the autumn storm with 5.93 milligrams per litre recorded in Warra Creek and 5.54 milligrams per litre in Crystal Creek. Sodium concentrations in Crystal Creek reached a minimum concentration of 1.84 milligrams per litre during the winter storm.

Figure 8.21: Winter storm displaying total potassium and total sodium concentrations.



8.7 Other metals

Neither storm caused any discernible pattern of changes in total copper concentrations (Figures 8.24 and 8.25). In both storms and in both Warra and Crystal creeks, peaks in total iron and manganese were evident prior to stream height peaks (Figures 8.22, 8.23, 8.24 and 8.25).

Maximum iron concentrations were recorded during the winter storm with 1310 micrograms per litre recorded in Warra Creek and 990 micrograms per litre in Crystal Creek. ANZECC (1996) regards 500 – 1000 micrograms per litre as a maximum level for the maintenance of healthy ecosystems.

Figure 8.22: Autumn storm displaying total iron concentrations.

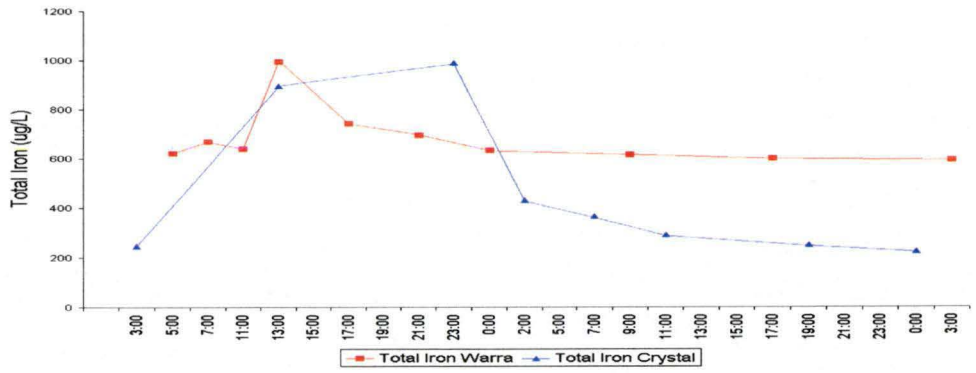
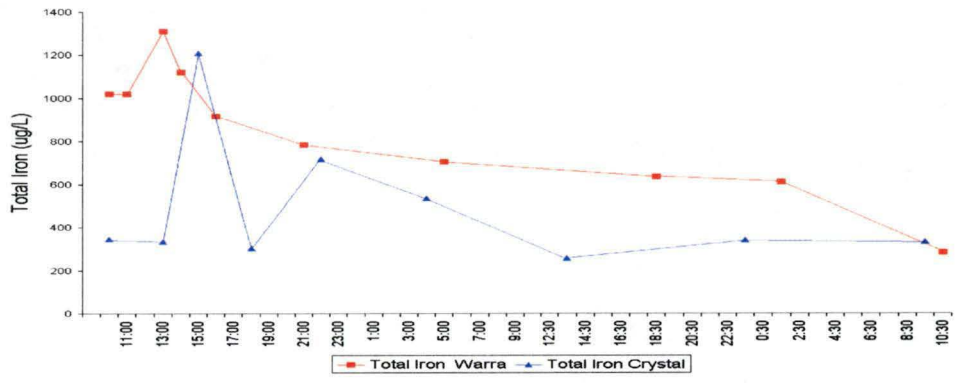


Figure 8.23: Winter storm displaying total iron concentrations.



Maximum concentrations of total copper were recorded in autumn, with 29 micrograms per litre in Warra Creek and 10 micrograms per litre in Crystal Creek. A minimum copper level of 5 micrograms per litre was recorded at Crystal Creek during the winter storm. Manganese maximums were recorded during winter, with 26 micrograms per litre at Warra Creek and 77 micrograms per litre recorded at Crystal Creek.

Figure 8.24: Winter storm displaying total copper and total manganese concentrations.

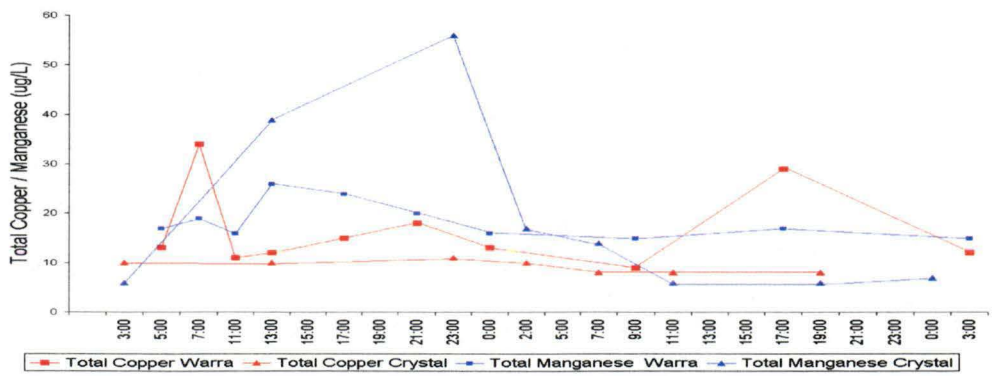
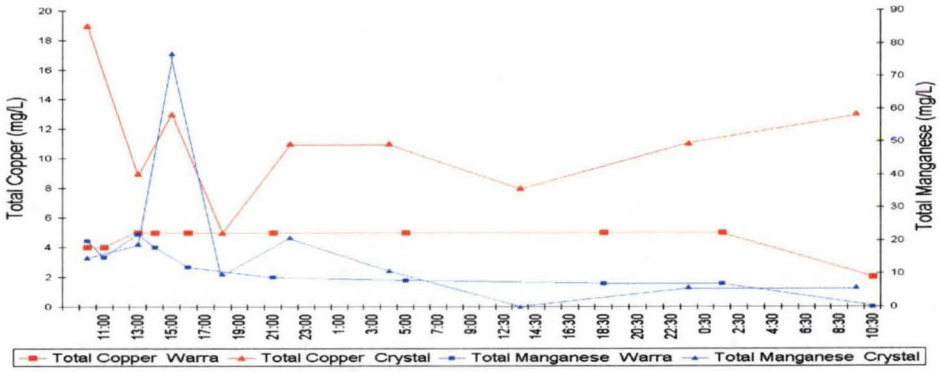


Figure 8.25: Winter storm displaying total copper and total manganese concentrations.



8.8 Summary

During both the autumn and winter storm in Warra and Crystal creeks parameter level increases began early on the rising limb of the hydrograph. This bell shaped pattern of sediment exhaustion occurs as a result of inorganic and organic material building up between storms in the catchment. This material is transported away by the first flush of quick flow generated by any oncoming storm. Once this initial supply is exhausted, levels slowly decline to pre-storm levels. Where parameter levels have declined with increased stage height, rainwater is causing a dilution of these particular parameters.

A clear pattern emerged of parameters that were affected by stage height and those that were not affected or showed a negative correlation. Parameters affected by stage height are turbidity, apparent colour, total dissolved and suspended solids, nitrogen, phosphorus, iron, manganese, nitrate + nitrite, nitrite, calcium (autumn only) and magnesium (autumn only). Parameters either, not affected by stage height or negatively affected, are conductivity, pH, ammonia, ortho-phosphate, copper, sulphate, calcium, magnesium, potassium and sodium.

In both creeks for one or both storms the stage height dependant parameters such as; turbidity, apparent colour, total nitrogen, phosphorus, iron, manganese and ortho-phosphate were all strong to very strongly correlated with each other. A major difference between the creeks is that in Warra Creek the above parameters were all correlated with total dissolved solids, while at Crystal Creek they were correlated with total suspended solids.

Most of the parameters affected by stage height reached maximum levels during the winter storm. Those parameters negatively affected by stage height reached higher levels during baseflow periods and attained minimum levels during the winter storm when stream groundwater inputs are at there lowest.

Ionic proportions in Warra Creek catchment ranged between $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ to $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, with increasing rainfall having minimal affect (except sodium, which decreased). In Crystal Creek ionic proportions were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. However, concentrations increased during the autumn storm and decreased during the winter storm. Concentration of calcium, magnesium and potassium were also higher in Crystal Creek catchment irrespective of stream heights.

These ionic proportions and differences in ionic concentrations indicate that the composition of water in Warra Creek is very similar to dilute seawater and is not affected by changes to stream heights. While in Crystal Creek some aspects of geochemical and related environmental influences are found. Calcium, magnesium and potassium increased concentrations during the autumn storm as new water flushed out old groundwater from across the catchment. However, during winter the catchment is already saturated and so concentrations are diluted by fresh new water entering from the winter storm event.

This chapter outlined the analysis of results from the storm sampling project. Parameters were divided into those where levels increased with higher stream heights and those that were not affected, or decreased with increased stream heights.

Chapter 9: Discussion

9.1 Introduction

The source of colour and nutrient enrichment in the pristine forested catchment of Warra Creek, and the reasons for the variation in water quality between Warra and Crystal creeks, are discussed. Results from this study and the review of information on water quality characteristics have resulted in the production of a range of expected parameter levels found within the pristine southern forests of Tasmania. In future it is recommended these guidelines be utilised for comparisons with other water quality result for the assessment of forestry impact management.

Water quality of Warra and Crystal creeks was correlated with stage height, with a decline in quality caused by increases in stream heights. During periods of low flow, water quality was worse in Warra than Crystal Creek, while at high flow, water quality was found to be similar between the two creeks. A grouping of water quality parameters were found to be either positively affected, unaffected or negatively affected by stage height. These correlations highlight the differences in water quality depending on the time of sample collection and the hydroclimatic condition of the catchment.

9.2 Source of colour and nutrient enrichment in Warra Creek

Results from the three projects indicate that the source of colour and associated nutrient enrichment can be attributed to the headwaters of Warra Creek catchment, in particular the proportion of catchment contributing to Warra site 2. The catchment snapshot water sampling results demonstrate Warra site 2 as having the highest median levels of turbidity, apparent colour, total nitrogen, phosphorus, iron, manganese, nitrite, ammonia and nitrate + nitrite. When these parameters were assessed per hectare of contributing catchment above each site, Warra site 2 was found to have at least double the levels per hectare of the remaining catchment. By comparison, Crystal Creek was found to have extremely low levels of the above mentioned parameters.

In both Warra and Crystal creeks, apparent colour was strongly positively correlated with stage height and showed very strong positive correlations with turbidity, total nitrogen, phosphorus, iron, manganese, nitrite and ortho-phosphate. This association of colour with other water quality parameters was also observed by Mitchell and McDonald (1995), who suggested mobilisation of related parameters follow similar environmental processes such as water discolouration. Mitchell and McDonald (1995) attributed high water parameter levels to catchments with organic rich soils on south facing slopes on areas of $< 5°$. This prediction of coloured waters being associated with areas of prolonged water contact and decomposing organic matter (vegetation, litter, humus and soils) was successfully tested by Gippel (1987) and observed in a variety of studies (Boughton 1970), (Hongve 1999) and (Swaine et al. 1993). This prediction also appears to hold true for the catchment of Warra Creek.

The headwaters of Warra Creek catchment, especially around site 2 are recognisably different to the remainder of the catchment. The area surrounding site 2 contains a large proportion of sedimentary rock with associated yellow brown gley soils, was burnt in 1934 by a severe fire, slope is relatively flat and vegetation composed of low *Eucalyptus nitida* wet and mixed scrub.

Organic matter and various minerals, particularly iron oxides, produce colour in soils, therefore darker colours are an indicator of increased organic matter in the soil (Grant et al. 1995). Two major soil types are found in the upper portion of Warra Creek catchment, yellow brown gley soils and red brown clayey soils. The yellow brown gley soils occur in the majority of the catchment area associated with Warra site 2 and to a lesser extent are found within the sub-catchment of Warra site 1. Red brown clayey soils are dispersed between the yellow brown gley soils and are found throughout the rest of Warra Creek catchment. Greyish soils in lower horizons reflect anaerobic waterlogged conditions, (causing mobilisation of iron) while mottling and organic cutans (iron oxides) in red brown clayey soil are indicative of seasonal waterlogging due to imperfect drainage (Grant et al. 1995). Both soil types and the organic soil found around Warra site 4 and the weir have a large organic layer with abundant litter. Soil types and locations within the Warra Creek catchment therefore show an organic rich soil with seasonal waterlogging of selected areas and a large area of saturated yellowish brown sandy gley soil on the plateau in the headwaters of the catchment.

High rainfall, moderate slope (indicated by Figures 5.11 and 5.12), saturated soils and vegetation composition, consistent with poorly drained sites, indicated an elevated water table. This highly organic soak area located in the top of Warra Creek catchment (consistent with the Elsenbeer (2001) model) results in elevated levels of decomposition from the upper organic nutrient rich leaf and litter layers.

During baseflow periods a slow consistent leaching of discoloured water, associated humic substances and iron oxides occurs from land associated with Warra site 2 and to a lesser extent Warra site 1. This material steadily decreases in concentration with altitude. However, in the case of turbidity, ammonia and total phosphorus, levels were often higher in the lower two sites of Warra Creek than the middle site. This increase is due to the high component of organic soils in this portion of the catchment (Figure 5.10), which in the lower portion of Warra Creek catchment is sourced directly from organic soils resulting in a decrease in water quality.

Stream height had a significant impact on the water quality of the measured sites, with levels of turbidity, apparent colour, total nitrogen, phosphorus and iron increasing with stage height. During high flow events, levels at Warra site 2 increased by about a third, the remaining catchment sites at least double and Crystal Creek catchment increased by at least four times baseflow levels. Rising stream height therefore results in a degradation of water quality across all sample sites. Without measuring water quality from a variety of sites in Crystal Creek catchment, the source of these parameter increases cannot be quantified. However, results from this study in Warra Creek catchment suggest that the flushing of accumulated organic material from across increased portions of the catchment also occur in Crystal Creek catchment, with percentage of contributing catchment depending on the amount of rain.

The hypothesis that "the difference in water quality between Warra and Crystal creeks is due to a much greater contact time between water and organic matter in Warra Creek catchment" was proved to be correct. This soaked organic matter causes the continued leaching of decomposing material and weathering products during periods of both low and high stream heights. High levels of colour and nutrients are linked to the headwaters of the catchment, due to the environmental factors associated with Warra site 2. However, some other parameters, turbidity in

particular, are also sourced from the lower portion of the catchment in areas of extensive organic soils. Organic matter and mineral chemicals are continually leached during baseflow conditions but peak in times of high flow, as high drainage movement created by increased rainfall produces a faster export of the organic rich waters. Crystal Creek does not have these unusual conditions found above Warra sites 1 and 2 and therefore while following a similar pattern of leaching during high rainfall events, does not reach the high levels found in Warra Creek during baseflow periods.

9.3 Explanation of the differences in water quality between Warra and Crystal creek catchments

Prior to this study Warra and Crystal creek catchments were assumed to be relatively homogenous. Both catchments consist of a similar size of pristine undisturbed land, that drain water from Mount Weld in the Tasmania's Wilderness World Heritage area (aside from thirty hectares of regenerated forest in Crystal Creek catchment). However, through this study several important differences between the two catchments were found.

Aspect and topography of the Warra and Crystal creek catchments are quite different. Warra Creek catchment faces south and has a relatively flat plateau in the headwaters of the catchment, while Crystal Creek catchment faces east and has a moderate incline leading to an area of steep land in the catchment headwaters. Geology and related soils are relatively similar, with both catchments having a combination of Permian sedimentary rocks and Jurassic dolerite. Jurassic dolerite in Crystal Creek catchment is dominantly derived from Quaternary talus. Locations of these vary between the catchments, with Warra Creek catchment (unlike Crystal Creek catchment), containing a large percentage of sedimentary material in the headwaters of the catchment. Patches of Warra Creek catchment were extensively burnt in 1934 and 1974, in contrast Crystal Creek catchment that has remained unburnt since at least 1850 (Hickey et al. 1998). These environmental factors are reflected in the hydroclimatic conditions of the catchments and have resulted in significantly different vegetation compositions.

The type of vegetation present within a catchment specifically affects soil dynamics, drainage intensity and the biochemistral functioning of the ecosystem (Leflong et al. 1990) and plays a major role in determining the water quality of a catchment (Bowman et al. 1986). This vegetation and its associated litter has been demonstrated by Hongve et al. (2000) to contribute the major percentage of dissolved substances in soil and surface water. In the Warra LTER site, Swain et al. (1993) noted that litter type and density varied between streams and was determined by floristic composition and density. This difference in vegetation composition between Warra and Crystal Creek catchments is reflected in the water quality data that emerged from the two catchments.

The amount of discharge within a particular creek determines the flowpath of the water through the catchment and therefore the chemical composition of that water (Church 1997). This was observed in the data with seasonal trends evident in both Warra and Crystal creeks. Rainfall, turbidity and apparent colour are positively correlated with stage height and apparent colour is positively correlated with many other water quality parameters, a seasonal trend of decreasing water quality during the winter months therefore occurs. Water quality also constantly changes due to the high frequency of storms that occur in the Warra LTER site (Figures 6.1, 6.2, 6.3 and 6.4). However, during summer baseflow periods, pH, temperature, electrical conductivity, chloride, sulphate, calcium, magnesium and sodium all form elevated peaks. The two creeks therefore display very similar trends in water quality results. The only difference occurred in the actual levels of these measured parameters.

Levels of chemical and physical parameters at Warra and Crystal creek during 2001, over a range of flow conditions are summarised in Table 9.1. This table shows that Crystal Creek has lower concentrations of nutrients, metals, lower minimum levels of turbidity and apparent colour (recorded during low stage height periods) with a higher range of values for all major ions. As stream height increased after rainfall from storms, parameters significantly increased to reach levels similar to those observed in Warra Creek (except for apparent colour, total nitrogen and total iron). Ionic proportions were similar to dilute seawater in both catchments with Warra Creek ranging between $Na^+ > Ca^{2+} > Mg^{2+}$ and $Na^+ > Mg^{2+} > Ca^{2+}$, and Crystal Creek having a dominance order of $Na^+ > Ca^{2+} > Mg^{2+}$. Ionic concentrations were

higher in Crystal Creek catchment due to a higher proportion of geochemical and related environmental influences in the catchment.

Warra and Crystal creek catchments have different water quality because of the diverse environmental factors that combine to form the catchments. Higher baseflow parameter levels in Warra Creek are due to the prolonged contact of water with organic matter and the associated biological processes. Crystal Creek catchment does not have this unusual characteristic, resulting in water being filtered through mineral soil instead of organic soil during low flow periods. However, during periods of high flow, "run-off" from organic surface layers, flush the accumulated build up of suspended sediments and solutes from across the catchment, resulting in water quality that is similar to Warra creek. This explanation is supported by the fact that total dissolved solids, which originate from rock weathering and the atmosphere, are strongly positively correlated with turbidity, apparent colour and most nutrients in Warra Creek, but not Crystal Creek. The opposite is true for total suspended solids, which originate from the surface of the catchment, with correlations only found in Crystal Creek.

9.4 Natural water quality variations in the southern forests of Tasmania

Warra and Crystal creeks are examples of two forested catchments with a range of water quality characteristics. Warra Creek has low pH levels and reaches elevated levels of turbidity, apparent colour, total nitrogen and iron during baseflow conditions, while Crystal Creek remains at very low levels. However, both creeks reach high parameter levels during periods of increased rain from storm events. Concentrations of peak storm levels, when compared to benchmark water quality guidelines (ANZECC 1996) and (NHMRC 2000) are still considered very clean. Only turbidity, apparent colour, total nitrogen and iron reach threshold levels during peak storm flow events.

The results from this study can therefore only be used as a comparison for other forested creeks and streams in the southern forests of Tasmania. Table 9.1 contains the range of minimum and maximum parameter levels observed in Warra and Crystal

creeks over the three projects, during 2001. The combined column encompasses minimum and maximum levels in both Warra and Crystal creeks.

Table 9.1: Range of parameter levels in Warra and Crystal creeks and expected range of levels (combined) for creeks and rivers in the southern forests of Tasmania.

Parameter	Warra Creek	Crystal Creek	Combined
Electrical conductivity (µS/cm)	34.0 – 56.5	29.8 – 75.7	29.8 – 75.7
pH (H^+)	3.5 - 6.1	5.3 – 6.8	3.5 – 6.8
Temperature (°C)	5.5 - 12	5.5 –12.5	5.5 – 12.5
Turbidity (NTU)	0.4 – 12.2	0 – 14.1	0.0 – 14.1
Apparent colour (CU)	66 - 337	4 - 142	4 - 337
Total nitrogen (µg/L)	158 - 756	79 – 451	79 - 756
Ammonia (µg/L)	13 - 282	9.0 - 142	9 - 282
Nitrate + nitrite (µg/L)	< 2 - 19	< 2 – 12	< 2 - 19
Nitrite (µg/L)	< 2 - 10	< 2 - 3	< 2 - 10
Total phosphorus (µg/L)	< 5 - 19	< 5 - 14	< 5 - 19
Ortho-phosphate (µg/L)	< 2 - 16	< 2 - 3	< 2 - 16
Chloride (mg/L)	4.0 - 10	5.3 – 10	4.0 - 10
Sulphate (mg/L)	0.4 – 1.6	0.5 – 1.2	0.4 – 1.6
Total calcium (mg/L)	0.3 – 1.3	0.76 – 3.1	0.3 – 3.1
Total potassium (mg/L)	0.15 – 0.38	0.19 – 0.35	0.15 – 0.38
Total magnesium (mg/L)	0.55 – 1.23	0.62 – 2.31	0.55 – 2.31
Total sodium (mg/L)	3.9 – 5.9	3.2 – 5.6	3.2 – 5.9
Total copper (µg/L)	< 2 - 2	< 2 - 2	< 2 - 2
Total iron (µg/L)	318 - 1310	92 - 1210	92 - 1310
Total manganese (µg/L)	< 2 - 26	< 2 - 77	< 2 - 77

This range of expected levels should be utilised by Forestry Tasmania and other organisations to assess potential water quality degradation resulting from forest management. If chemical and physical parameter levels exceed the ranges obtained through this study, Forestry Tasmania should investigate for natural catchment variations or look for forest harvesting or roading impacts. These variations to water quality parameter levels can then be better monitored or if necessary forestry impacts can be modified or fixed to prevent further water quality degradation.

This study has shown that pristine catchments can be significantly different to each other in terms of water quality, especially during low flow conditions. Therefore, the best way to monitor for declining water quality in catchments is through in depth assessments before and after any impacts. If catchments cannot be assessed before and after impacts, water sampling should be conducted during baseflow conditions. However, due to the high number of storms in southern Tasmania, baseflow levels are often rare, making the collection of samples during this period difficult.

The range of parameter levels provided in Table 9.1, can only be used as a benchmark with which to compare other water quality samples collected from the southern forests. It cannot replace in depth water monitoring data or be extrapolated to provide guidelines in areas outside the southern forest of Tasmania.

9.5 Conclusion

The aims and objectives of this study have now been successfully met. The source of water discolouration and associated nutrients in Warra Creek has been shown to be mainly from the headwaters of the catchment as a result of prolonged contact of water with organic matter, causing the continued leaching of decomposing material and weathering products. This phenomenon and differences in other associated environmental variables, causes the difference in water quality in Warra and Crystal creeks during periods of low flow, and explains the similar water quality in periods of high flow. The outcomes of this study need to be taken into account when considering forest management of catchments that contain a large percentage of organic matter.

Results from this study provide a reference tool when comparing other pristine forested catchments in southern forests of Tasmania. To gain a greater understanding of water quality in the southern forests of Tasmania, further investigations of Warra Creek catchment are needed. A focus on the influence that saturated organic matter has on parameter concentrations would provide greater insight on the underlying reasons for natural variations in water quality in forested catchments.

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Appendices

Appendix 1: Water quality guidelines (ANZECC 1996), unless otherwise stated (NHMRC 2000) and natural surface water concentration level and component sources (adapted from Bobbi 1996; Chessman 1992; Chapman 1996; Kruger 1994; Tiller 1995).

Component	Concentration guidelines	Natural sources
Physical		
Turbidity	<10% change from seasonal mean ≤5 NTU (NHMC, 2000) Low Tasmania mountain elevation level of < 5 Very elevated Tasmanian mountain level of >12 (Bobbi, 1996)	silt, clay, fine particles of organic and inorganic matter
Conductivity	1500 µS/cm Low mountain elevation level of < 20 Very elevated mountain level of >100 (Bobbi, 1996)	geology - total dissolved material (primarily mineral salts)
pH	6.5 - 8.5 Low elevation level of 6.0 – 7.5 Very elevated levels of < 5.0 - > 9.0 (Kruger, 1994)	atmosphere, geology and vegetation leachate
Temperature	0 – 30 degrees Celsius (Chapman, 1996)	atmosphere, latitude, altitude, slope, aspect, vegetation cover
Apparent colour	< 5 in clean waters > 300 in peaty waters > 50 at base flow levels (Bobbi, 1996) 200 CU are considered to be very high readings (Chessman, 1992)(Gallagher, 1996)	metallic irons (iron & manganese), humus and peat material, planktonic weeds and vegetation leachate
Nutrients		
Ammonia	< 100 µg/L typically < 200 µg/L in surface waters (Chapman, 1996)	breakdown of nitrogenous organic and inorganic matter, plant and animal excrement
Nitrate	< 10 mg/L usually found in surface waters (Chapman, 1996)	atmosphere, igneous rocks, plant and animal excrement
Nitrite	< 1.0 mg/L usually found in surface waters (Chapman, 1996)	breakdown of nitrate by denitrification processes
Total nitrogen	100 – 750 µg/L in freshwater Background levels of 70 µg/L Threshold levels of 150 µg/L (Tiller, 1995)	the sum of ammonium ion, nitrate and nitrite

Ortho-phosphate	Low elevation level of 8 µg/L Very elevated level at 50 µg/L (Kruger, 1994)	decomposition of organic matter
Total phosphorus	10 – 100 ug/L Background levels of 10 µg/L Threshold levels of 20 µ mg/L (Tiller, 1995)	combination of all phosphates and organically combined phosphorus -weathering of phosphorus bearing rocks
Major ions: anions		
Chloride	400 mg /L < 10 mg/L in surface waters (Bobbi, 1996)	atmosphere and weathering of some sedimentary rocks
Sulphate	400 mg/L 2 - 80 mg/L in surface waters (Bobbi, 1996)	atmosphere and weathering of some sedimentary rocks
Major ions: cations		
Total calcium	< 500 mg/L < 15 mg/L in surface waters (Bobbi, 1996)	weathering of rocks rich in calcium minerals, particularly areas rich in limestone and gypsum
Total potassium	< 500 mg/L < 10 mg/L in Tasmanian surface waters (Bobbi, 1996)	feldspars, clay minerals
Total magnesium	< 500 mg/L 1-100 mg/L in Tasmanian surface waters (Bobbi, 1996)	weathering of rocks containing feromagnesium minerals and some carbonate rocks
Total sodium	< 500 mg/L < 10 mg/L in Tasmanian surface waters (Bobbi, 1996)	feldspars, clay minerals
Metals		
Total copper	2 – 5 µg/ L	include weathering of copper minerals and native copper
Total iron	500 – 1000 µg/	weathering of igneous and sandstones rocks
Total manganese	< 100 µg/L	weathering of metamorphic and sedimentary rocks

Appendix 2: Soil profile descriptions from sites in Warra Creek catchment.

Site	Horizon	Depth (cm)	Description
1	O1	-31 to -30	Loose litter and leaves
1	O2	-30 to 0	2.5YR2.5/3 grading to 10YR2.5/3/4
2	*O1*	-1to 0	Loose litter and leaves
2	A1	0 to 3	Dark reddish brown (5YR3/3) organic material with abundant roots
2	B1	3 to 30	Silty clay loam (5YR5/6)
2	B2	30 to 60	Light clay (7.5YR5/6)
2	B3	60 to 70	Light clay on top of bedrock (7.5YR5/8)
3	O1	-31 to -30	Loose litter and leaves
3	O2	-30 to 0	2.5YR2.5/3 grading to 10YR2.5/3/4
4	O1	-1 to 0	Loose litter and leaves
4	A1	0-35	Silty clay loam (10YR4/4) grading to rock
5			Large fallen tree with broad plate like root system
6	*O1*	-1to 0	Loose litter and leaves
6	A1	1 to 7	Silty clay loam (10YR3/3)
6	B1	7 to 70	Silty clay loam to a light clay loam (10YR4/4 grading to 10YR3/4)
6	B2	70 to 90	Light clay grading to medium clay with depth (10YR3/4 grading to 5GY4/1 (GIEY))
7	*O1*	-5to -3	Loose litter and leaves
7	O2	-3 to 0	Very dark greyish brown organic material with abundant roots
7	A	0 to 8	Quartz gravelly loam (10YR3/2) with some sand and abundant roots present.
7	B21	8 to 15	Dark yellowish brown gritty loam (10YR4/4 grading to 10YR3/2)
7	B22	15 to 28	Dark yellowish brown gritty loam (10YR3/3 with 10YR4/4 mottles)
7	B22g	28 to 80+	Light greenish grey sandy loam with occasional coarse roots, extremely waterlogged GLEY that changes colour with depth. (GLEY 10Y7/1 grading to GLEY 10B6/1 and GLEY 10Y6/1)
8	*O1*	-1 to 0	Loose litter and leaves
8	A	0 to 10	Silty loam (7.5YR3/2)

Site	Horizon	Depth (cm)	Description
8	B1	10 to 100	Variable soil amongst dolerite boulder scree with abundant rooting throughout. Gravelly silty loam (7.5YR3/2)
9	*O1*	-5 to -3	Loose litter and leaves
9	O2	-3 to 0	Organic material
9	A	0 to10	Silty loam with gravel (2.5YR2.5/2 grading down to 2.5YR3/4) with abundant concentration of roots and organic matter.
9	B1	10 to 20	Silty loam with gravel(2.5YR4/6)
9	B2	20 to 28	Gravelly loam (10YR5/6 grading to 10YR4/6)
9	B3	28 to 33	Gritty loam (10 YR5/6) with iron oxide cutans (2.5YR2.5/1) around polyhedral peds (20 –50 mm)
9	B3	33 to 50	Sandy clay loam (10YR5/7)
10	*O1*	-1 to 0	Loose litter and leaves
10	*A*	0 to 10	Silty loam (2.5YR2.5/3 grading to (2.5YR2.5/4)
10	*B*	10 to 30	Sandy loam (2.5YR2.5/4)
11	*O1*	-1 to 0	Loose litter and leaves
11	*A*	0 to 8	Silty loam (2.5YR2/2)
11	*B*	8 to 40	Loam (2.5YR3/2)
12	*O1*	-1 to 0	Loose litter and leaves
12	*A*	0 to 18	Loam (5YR2.5/2)
12	*B1*	18 to 40	Sandy loam (10YR2.5/2)
12	*B2*	40 to 50	Gritty loam (2.5 YR4/4) with mottles (2.5YR6/6)
12	*B3*	50 to 55	Light clay loam (GLEY 10GY5/1)

Appendix 3: Summary statistics from fortnightly data collected during 2001.

	Rainfall Stand guage (mm)	Site	Flow mm	Temperature deg C	pH	Conductivity uS/cm	Turbidity NTU
No. readings	26	Crystal	27	26	27	27	27
Period of record	2001	Crystal	2001	2001	2001	2001	2001
Minimum	12.5	Crystal	120.0	5.5	5.3	30.2	0.0
25% Quartile	31.0	Crystal	190.0	6.1	5.9	36.3	0.4
Median	41.5	Crystal	260.0	7.8	6.3	47.7	0.5
75% Quartile	62.0	Crystal	300.0	10.0	6.4	52.5	1.1
Maximum	220	Crystal	420.0	12.5	6.8	75.7	6.7
Mean	57	Crystal	248.5	7.8	6.3	43.7	0.5
Total rainfall	1335						
No. readings		Warra	27	25	27	27	27
Period of record		Warra	2001	2001	2001	2001	2001
Min		Warra	43.0	5.5	4.1	36.2	0.4
25% Quartile		Warra	120.3	6.0	4.8	38.3	1.1
Median		Warra	191.5	7.0	5.1	43.1	1.4
75% Quartile		Warra	245.2	11.0	5.6	49.7	2.3
Max		Warra	794.0	12.0	6.1	56.5	8.2
Mean		Warra	227.5	8.2	5.1	44.1	1.8

Appendix 4: Correlation coefficients with significance levels highlighted for fortnightly parameters from Warra and Crystal creeks during 2001.

Warra Creek	Standguage	Flow	Turbidity	Conductivity	pH	Temperature
Standguage		0.765	0.2817	-0.2143	-0.5948	-0.324
		0.0001	0.2426	0.3784	0.0072	0.176
Flow			0.7479	-0.1809	-0.8344	-0.5761
			0.0002	0.4586	0	0.0098
Turbidity				0.1447	-0.4675	-0.3269
				0.5545	0.0436	0.1719
Conductivity					0.4562	0.4166
					0.0496	0.076
pH						0.724
						0.0005
Temperature						

	Crystal Flow	Warra flow	Rainfall
Crystal Flow		0.858	0.749
		0.000	0.000
Warra flow			0.765
			0.000
Rainfall			

Crystal Creek	Standguage	Flow	Turbidity	Conductivity	pH	Temperature
Standguage		0.749	0.392	-0.414	-0.765	-0.332
		0.000	0.097	0.078	0.000	0.165
Flow			0.593	-0.753	-0.799	-0.518
			0.007	0.000	0.000	0.023
Turbidity				-0.164	-0.335	-0.216
				0.502	0.161	0.375
Conductivity					0.749	0.760
					0.000	0.000
pH						0.646
						0.003
Temperature						

Appendix 5: Raw data for Warra and Crystal creeks from fortnightly sampling during 2001.

Date	stand guage	Site	Time	Flow	Temperature	pH	Conductivity	Turbidity
	mm		EST	mm	deg C		uS/cm	NTU
7/01/2001		Crystal	16:25	180	12	6.08	61.6	0.5
23/01/2001	43	Crystal	9:30	160	10	6.46	70.3	0.2
5/02/2001	13	Crystal	9:53	120	11.5	6.57	70.9	0.4
20/02/2001	36	Crystal	10:49	140	12.5	6.61	72.4	0.6
7/03/2001	13	Crystal	10:34	120	11	6.8	75.7	0.2
20/03/2001	35	Crystal	12:30	160	11.5	6.49	67.4	0.5
3/04/2001	37	Crystal	11:39	200	7.5	6.48	53.6	1.0
19/04/2001	50	Crystal	11:39	320	8	6.39	44.1	2.0
2/05/2001	15	Crystal	14:30	160	6.5	6.29	51.5	0.5
17/05/2001	41	Crystal	10:43	280		5.75	45.7	1.7
28/05/2001	32	Crystal	10:55	200	7	6.24	44.1	1.2
12/06/2001	27	Crystal	12:16	200	6	6.48	43.7	0.1
25/06/2001	130	Crystal	10:17	420	6	5.82	40.2	6.7
10/07/2001	42	Crystal	10:52	200	5.5	6.34	43.5	0.0
23/07/2001	67	Crystal	12:10	200	7.5	6.07	42.4	0.4
2/08/2001	36	Crystal	10:25	300	6	5.59	30.2	1.3
20/08/2001	220	Crystal	12:00	380	5.5	5.28	35.4	0.9
4/09/2001	48	Crystal	10:25	280	5.5	5.91	35.6	0.0
17/09/2001	63	Crystal	10:55	380	5.5	5.8	31.3	1.5
1/10/2001	29	Crystal	12:05	280	7	6.34	40.2	0.7
16/10/2001	115	Crystal	10:05	300	6.5	5.81	34.4	0.6
30/10/2001	130	Crystal	10:40	380	8	5.72	32.8	1.1
13/11/2001	58	Crystal	13:52	320	8	6.03	32.4	0.4
28/11/2001	60	Crystal	9:33	290	10	6.25	37	0.6
11/12/2001	31	Crystal	11:28	200	9.5	6.37	48.4	0.3
20/12/2001	29	Crystal	9:50	260	8	6.31	40.2	0.5
2/01/2002	72	Crystal	13:48	280	10	6.37	45.1	0.4

Date	Site	Time	Flow	Temperature	pH	Conductivity	Turbidity
		EST	mm	deg C		uS/cm	NTU
7/01/2001	Warra	18:15	115	11.7	5.54	50	0.8
23/01/2001	Warra	10:25		10	6.05	53.5	0.4
5/02/2001	Warra	10:46		11.5	6.11	54.6	1.1
20/02/2001	Warra	13:00	6	12	6.07	55.2	1.4
7/03/2001	Warra	13:25	43	11	6.03	56.5	0.8
20/03/2001	Warra	13;55	71	12	5.92	53.6	1.2
3/04/2001	Warra	13:00	133	7	5.17	49	1.5
19/04/2001	Warra	13:01	398		4.47	49.3	2.5
2/05/2001	Warra	12:40	116	6	5.4	43.9	1.4
17/05/2001	Warra	11:29	201		5.04	45.2	3.1
28/05/2001	Warra	11:50	169	7	5.08	43.2	1.5
12/06/2001	Warra	13:46	182	6	5.04	43.3	1.1
25/06/2001	Warra	11:50	794	5.5	4.31	50.3	8.2
10/07/2001	Warra	11:36	219	6.5	5.01	43.1	1.0
23/07/2001	Warra	13:30	270	7	5.02	42.9	1.4
2/08/2001	Warra	12:05	361	5.5	4.62	37.3	2.5
20/08/2001	Warra	11:30	584	5.5	4.09	39.1	1.0
4/09/2001	Warra	12:15	210	5.5	4.99	38	1.6
17/09/2001	Warra	12:10		6	4.15	38.6	3.0
1/10/2001	Warra	13:00	246	7	5.15	39.2	2.7
16/10/2001	Warra	10:47	243	7	5.68	37.4	1.0
30/10/2001	Warra	11:20		7	4.22	37	3.0
13/11/2001	Warra	11:05		8	4.5	36.2	1.1
28/11/2001	Warra	11:55	233	10	4.9	37.2	2.0
11/12/2001	Warra	13:20	152	11	5.3	40.2	0.4
20/12/2001	Warra	10:15	100	9	5.57	37	1.4
2/01/2002	Warra	14:11	160	11	5.39	39.8	1.4

Appendix 6: Summary statistics from snapshot data collected during 2001.

Site	Statistics	pH	Conductivity uS/cm	Turbidity NTU	Apparent Colour CU	Ammonia ug/L	Nitrate+Nitrite ug/L	Nitrite ug/L
Warra #1	Min	4.10	34.0	0.8	72	17.0	2.0	2.0
Warra #1	25% Quartile	4.45	34.3	1.1	83	20.0	6.5	2.0
Warra #1	Median	4.63	35.2	1.3	91	21.0	8.5	2.0
Warra #1	75% Quartile	4.80	37.9	1.4	114	24.3	9.5	2.8
Warra #1	Max	5.51	43.2	1.7	173	34.0	11.0	5.0
Warra #2	Min	3.55	38.7	1.8	198	25.0	2.0	2.0
Warra #2	25% Quartile	3.73	39.7	1.9	239	25.0	10.3	4.3
Warra #2	Median	3.83	40.8	2.1	279	26.5	14.5	7.0
Warra #2	75% Quartile	3.90	41.8	2.4	314	30.0	16.8	9.3
Warra #2	Max	4.41	42.0	3.1	337	36.0	19.0	10.0
Warra #3	Min	3.71	35.6	0.4	93	13.0	2.0	2.0
Warra #3	25% Quartile	4.06	37.1	0.9	116	15.3	8.8	2.8
Warra #3	Median	4.19	38.2	1.2	135	31.0	11.0	3.5
Warra #3	75% Quartile	4.44	39.5	1.5	171	51.8	11.3	4.8
Warra #3	Max	5.12	41.5	1.9	244	69.0	12.0	7.0
Warra #4	Min	3.83	38.9	1.1	78	39.0	2.0	2.0
Warra #4	25% Quartile	4.37	39.4	1.3	90	44.3	7.3	2.0
Warra #4	Median	4.61	40.5	1.4	100	46.0	9.5	2.5
Warra #4	75% Quartile	4.88	42.3	1.7	132	47.5	10.3	3.8
Warra #4	Max	5.42	45.4	2.6	210	52.0	11.0	6.0
Warra Weir	Min	4.01	38.0	0.3	66	10.0	2.0	2.0
Warra Weir	25% Quartile	4.76	39.6	0.8	78	16.0	7.3	2.0
Warra Weir	Median	5.07	41.5	1.2	84	27.5	10.0	2.5
Warra Weir	75% Quartile	5.16	43.0	1.8	119	38.3	11.0	3.8
Warra Weir	Max	5.30	43.5	2.8	218	42.0	11.0	6.0
Crystal	Min	4.99	29.8	0.4	4	9.0	2.0	2.0
Crystal	25% Quartile	5.35	39.3	0.4	11	14.3	3.5	2.0
Crystal	Median	5.76	44.2	0.5	15	17.5	6.5	2.0
Crystal	75% Quartile	6.05	49.3	1.0	34	31.3	9.8	2.0
Crystal	Max	6.07	59.2	2.5	89	68.0	12.0	2.0

Site	Statistics	Total Nitrogen ug/L	Ortho-Phosphate ug/L	Total Phosphorous ug/L	Chloride mg/L	Sulphate mg/L
Warra #1	Min	182.0	2.00	5.0	5.3	0.8
Warra #1	25% Quartile	203.8	2.00	5.0	6.9	0.9
Warra #1	Median	214.0	2.00	6.5	7.7	0.9
Warra #1	75% Quartile	248.3	2.25	8.0	8.3	0.9
Warra #1	Max	342.0	3.00	8.0	9.0	1.0
Warra #2	Min	335.0	2.00	5.0	4.0	0.4
Warra #2	25% Quartile	362.0	2.00	6.5	5.8	0.5
Warra #2	Median	396.0	2.50	8.0	6.5	0.6
Warra #2	75% Quartile	437.0	3.25	9.3	7.2	0.8
Warra #2	Max	485.0	4.00	10.0	8.6	1.4
Warra #3	Min	218.0	2.00	5.0	5.5	0.7
Warra #3	25% Quartile	222.5	2.00	5.0	6.1	0.8
Warra #3	Median	229.0	2.00	6.5	7.2	0.8
Warra #3	75% Quartile	289.5	2.25	7.3	8.4	0.9
Warra #3	Max	456.0	3.00	8.0	9.5	1.0
Warra #4	Min	209.0	2.00	5.0	6.7	0.9
Warra #4	25% Quartile	210.5	2.00	5.8	8.4	1.0
Warra #4	Median	213.5	2.00	8.0	9.4	1.0
Warra #4	75% Quartile	261.5	2.25	10.0	9.8	1.1
Warra #4	Max	399.0	3.00	10.0	9.9	1.2
Warra Weir	Min	158.0	2.00	5.0	6.4	0.9
Warra Weir	25% Quartile	158.0	2.00	5.0	8.9	1.0
Warra Weir	Median	175.5	2.00	6.0	9.9	1.1
Warra Weir	75% Quartile	251.5	2.25	8.3	10.0	1.1
Warra Weir	Max	427.0	3.00	12.0	10.0	1.1
Crystal	Min	79.0	2.00	5.0	5.3	0.5
Crystal	25% Quartile	83.5	2.00	5.0	6.8	0.9
Crystal	Median	106.5	2.00	5.0	7.5	1.1
Crystal	75% Quartile	156.5	2.25	5.8	7.8	1.1
Crystal	Max	242.0	3.00	8.0	8.3	1.2

Site	Statistics	Total Calcium mg/L	Total Potassium mg/L	Total Magnesium mg/L	Total Sodium mg/L	Total Iron ug/L
Warra #1	Min	0.61	0.18	0.67	4.31	458.0
Warra #1	25% Quartile	0.63	0.21	0.71	4.42	462.5
Warra #1	Median	0.64	0.24	0.74	4.69	473.0
Warra #1	75% Quartile	0.81	0.27	0.87	5.02	490.8
Warra #1	Max	1.33	0.30	1.23	5.28	517.0
Warra #2	Min	0.33	0.21	0.55	3.93	568.0
Warra #2	25% Quartile	0.42	0.23	0.58	4.25	579.3
Warra #2	Median	0.46	0.26	0.63	4.38	583.5
Warra #2	75% Quartile	0.53	0.30	0.69	4.53	589.5
Warra #2	Max	0.72	0.38	0.81	4.92	606.0
Warra #3	Min	0.52	0.15	0.67	4.71	444.0
Warra #3	25% Quartile	0.59	0.19	0.72	4.76	462.0
Warra #3	Median	0.61	0.23	0.75	4.82	470.0
Warra #3	75% Quartile	0.68	0.27	0.81	5.00	503.0
Warra #3	Max	0.88	0.34	1.00	5.38	596.0
Warra #4	Min	0.69	0.17	0.81	5.02	373.0
Warra #4	25% Quartile	0.72	0.19	0.81	5.24	392.5
Warra #4	Median	0.74	0.24	0.85	5.35	410.5
Warra #4	75% Quartile	0.87	0.29	0.94	5.46	456.8
Warra #4	Max	1.22	0.33	1.10	5.68	561.0
Warra Weir	Min	0.63	0.17	0.78	4.95	318.0
Warra Weir	25% Quartile	0.69	0.21	0.80	5.31	331.5
Warra Weir	Median	0.72	0.23	0.82	5.47	350.5
Warra Weir	75% Quartile	0.73	0.27	0.85	5.58	416.5
Warra Weir	Max	0.74	0.34	0.88	5.83	571.0
Crystal	Min	0.76	0.19	0.62	3.18	92.0
Crystal	25% Quartile	1.35	0.20	1.15	4.30	104.0
Crystal	Median	1.70	0.20	1.42	4.77	150.0
Crystal	75% Quartile	2.17	0.24	1.72	5.04	231.8
Crystal	Max	3.08	0.35	2.31	5.59	351.0

Appendix 7: Raw data for Warra and Crystal creeks from snapshot sampling during 2001.

	Warra 1	Warra 2	Warra 3	Warra 4	Warra Weir	Crystal
Date/Time	14/05/2001 12:03	14/05/2001 11:50	14/05/2001 2:00	15/05/2001 12:10	15/05/2001 11:30	15/05/2001 11:00
Turbidity (NTU)	0.8	1.8	0.4	1.1	0.3	0.4
Conductivity (uS/cm)	43.2	42	41.5	45.4	43.5	59.2
pH	5.51	4.41	5.12	5.42	5.3	6.04
Apparent Colour (CU)	72	198	93	78	66	4
Chloride (mg/L)	9	8.6	9.5	9.9	10	8.3
Sulphate (mg/L)	0.88	0.59	0.88	0.92	1.1	1.2
Ammonia (ug-N/L)	21	25	46	46	10	19
Nitrate + Nitrite (ug-N/L)	11	13	11	11	11	12
Nitrite (ug-N/L)	2	5	3	2	2	2
Ortho-Phosphate (ug-N/L)	2	4	2	2	2	3
Total Nitrogen (ug/L)	182	335	224	211	158	85
Total Phosphorous (ug/L)	5	10	7	10	7	5
Total Copper (ug/L)	1	1	1	1	1	1
Total Iron (ug/L)	482	584	444	422	336	92
Total Calcium (mg/L)	1.33	0.72	0.88	1.22	0.74	3.08
Total Potassium (mg/L)	0.26	0.24	0.25	0.27	0.24	0.35
Total Magnesium (mg/L)	1.23	0.81	1	1.1	0.84	2.31
Total Sodium (mg/L)	5.28	4.92	5.38	5.68	5.43	5.59

	Warra 1	Warra 2	Warra 3	Warra 4	Warra Weir	Crystal
	23/07/2001 13:50	23/07/2001 13:25	23/07/2001 12:00	23/07/2001 10:15	23/07/2001 13:30	23/07/2001 12:20
Turbidity (NTU)	1.2	2.1	1.1	1.3	1.4	0.4
Conductivity (uS/cm)	36.1	41.5	38.8	41.3	42.9	42.4
pH	4.56	3.86	4.18	4.55	5.02	6.07
Apparent Colour (CU)	87	252	124	94	86	16
Chloride (mg/L)	8	6.7	6.3	9.7	10	7.6
Sulphate (mg/L)	1	1.4	0.69	1	1.1	1.1
Ammonia (ug-N/L)	34	25	13	46	37	16
Nitrate + Nitrite (ug-N/L)	9	19	11	10	11	9
Nitrite (ug-N/L)	2	9	4	3	2	2
Ortho-Phosphate (ug-N/L)	3	3	3	3	3	2
Total Nitrogen (ug/L)	217	421	234	209	193	79
Total Phosphorous (ug/L)	8	7	6	6	5	8
Total Copper (ug/L)	1	1	1	1	1	1
Total Iron (ug/L)	458	606	472	399	365	192
Total Calcium (mg/L)	0.64	0.45	0.61	0.75	0.72	1.54
Total Potassium (mg/L)	0.22	0.27	0.2	0.2	0.22	0.2
Total Magnesium (mg/L)	0.75	0.65	0.75	0.88	0.88	1.32
Total Sodium (mg/L)	4.93	4.35	4.77	5.31	5.5	4.68

	Warra 1	Warra 2	Warra 3	Warra 4	Warra Weir	Crystal
	17/08/2001 11:00	17/08/2001 10:50	17/08/2001 12:00	17/08/2001 13:45	17/08/2001 9:40	17/08/2001 9:15
Turbidity (NTU)	1.7	3.1	1.9	2.6	2.8	2.5
Conductivity (uS/cm)	34	40	37.6	38.9	38	29.8
pH	4.1	3.55	3.71	3.83	4.01	4.99
Apparent Colour (CU)	173	337	244	210	218	89
Chloride (mg/L)	5.3	4	5.5	6.7	6.4	5.3
Sulphate (mg/L)	0.92	0.6	1	1.2	0.89	0.48
Ammonia (ug-N/L)	17	28	69	39	42	9
Nitrate + Nitrite (ug-N/L)	8	16	12	9	9	4
Nitrite (ug-N/L)	5	10	7	6	6	2
Ortho-Phosphate (ug-N/L)	2	2	2	2	2	2
Total Nitrogen (ug/L)	342	485	456	399	427	242
Total Phosphorous (ug/L)	8	9	8	10	12	5
Total Copper (ug/L)	1	1	1	1	1	1
Total Iron (ug/L)	517	568	596	561	571	351
Total Calcium (mg/L)	0.61	0.33	0.61	0.69	0.71	0.76
Total Potassium (mg/L)	0.3	0.38	0.34	0.33	0.34	0.19
Total Magnesium (mg/L)	0.67	0.55	0.74	0.81	0.8	0.62
Total Sodium (mg/L)	4.31	3.93	4.71	5.02	4.95	3.18

	Warra 1	Warra 2	Warra 3	Warra 4	Warra Weir	Crystal
	6/12/2001: 10:55	6/12/2001: 10:50	6/12/2001: 11:40	6/12/2001: 13:30	6/12/2001: 14:00	6/12/2001: 14:30
Turbidity (NTU)	1.3	2	1.3	1.4	1	0.5
Conductivity (uS/cm)	34.3	38.7	35.6	39.6	40.1	46
pH	4.69	3.79	4.2	4.67	5.11	5.48
Apparent Colour (CU)	94	306	146	106	82	13
Chloride (mg/L)	7.4	6.3	8	9	9.7	7.3
Sulphate (mg/L)	0.76	0.38	0.79	0.98	1.1	1
Ammonia (ug-N/L)	21	36	16	52	18	68
Nitrate + Nitrite (ug-N/L)	2	2	2	2	2	2
Nitrite (ug-N/L)	2	2	2	2	2	2
Ortho-Phosphate (ug-N/L)	2	2	2	2	2	2
Total Nitrogen (ug/L)	211	371	218	216	158	128
Total Phosphorous (ug/L)	5	5	5	5	5	5
Total Copper (ug/L)	1	1	1	1	1	1
Total Iron (ug/L)	464	583	468	373	318	108
Total Calcium (mg/L)	0.63	0.46	0.52	0.73	0.63	1.86
Total Potassium (mg/L)	0.18	0.21	0.15	0.17	0.17	0.2
Total Magnesium (mg/L)	0.72	0.6	0.67	0.81	0.78	1.52
Total Sodium (mg/L)	4.45	4.4	4.87	5.39	5.83	4.86

Appendix 8: Correlation coefficients with significance levels highlighted for autumn storm parameters from Warra Creek during 2001.

	Flow	Turbidity	Conductivity	pH	Colour	TDS	TSS	Total N	Ammonia	Nitrate+nitrite	Nitrite	Total P	Ortho-P	Chloride	Sulphate	Ca	Mg	K	Na	Cu	Fe	Mn
Flow		0 242	0 731	-0 647	0 512	0 246	0 003	0 479	0 149	-0 010	0 209	0 369	0 369	0 522	0 370	0 108	0 513	0 353	0 563	0 017	0 184	-0 001
		0 644	0 099	0 165	0 299	0 639	0 995	0 337	0 779	0 985	0 692	0 471	0 471	0 288	0 470	0 838	0 298	0 492	0 245	0 974	0 727	0 998
Turbidity			0 261	-0 422	0 917	0 982	0 681	0 888	-0 072	0 952	0 751	0 972	0 972	-0 028	-0 315	0 500	0 825	0 622	0 722	0 491	0 955	0 930
			0 617	0 405	0 010	0 001	0 136	0 018	0 892	0 003	0 085	0 001	0 001	0 958	0 544	0 312	0 043	0 187	0 105	0 323	0 003	0 007
Conductivity				-0 953	0 545	0 248	-0 295	0 595	0 456	0 105	0 583	0 407	0 407	0 926	0 757	0 016	0 635	0 448	0 688	-0 058	0 176	-0 025
				0 003	0 264	0 636	0 570	0 213	0 363	0 843	0 225	0 424	0 424	0 008	0 081	0 976	0 175	0 374	0 131	0 913	0 739	0 963
pH					-0 658	-0 448	0 153	-0 666	-0 271	-0 292	-0 723	-0 554	-0 554	-0 881	-0 713	-0 037	-0 698	-0 359	-0 736	-0 062	-0 317	-0 149
					0 155	0 373	0 772	0 149	0 604	0 575	0 104	0 255	0 255	0 020	0 111	0 944	0 123	0 485	0 096	0 907	0 540	0 779
Colour						0 904	0 394	0 977	-0 060	0 843	0 857	0 982	0 982	0 249	-0 049	0 604	0 968	0 616	0 928	0 580	0 911	0 811
						0 013	0 440	0 001	0 911	0 035	0 029	0 001	0 001	0 634	0 926	0 204	0 002	0 193	0 008	0 228	0 012	0 051
TDS							0 685	0 840	-0 206	0 934	0 749	0 961	0 961	-0 015	-0 266	0 447	0 784	0 474	0 693	0 511	0 925	0 911
							0 134	0 037	0 695	0 006	0 087	0 002	0 002	0 978	0 611	0 374	0 065	0 342	0 127	0 301	0 008	0 012
TSS								0 316	-0 146	0 586	0 054	0 515	0 515	-0 516	-0 650	0 030	0 187	0 323	0 032	0 048	0 557	0 645
								0 542	0 783	0 222	0 919	0 295	0 295	0 295	0 162	0 955	0 723	0 532	0 952	0 929	0 251	0 167
Total Nitrogen									0 120	0 823	0 873	0 952	0 952	0 305	-0 017	0 612	0 987	0 744	0 942	0 520	0 890	0 775
									0 821	0 044	0 023	0 003	0 003	0 557	0 974	0 197	0 000	0 090	0 005	0 291	0 017	0 070
Ammonia										-0 186	-0 017	-0 110	-0 110	0 468	0 354	-0 353	0 061	0 646	0 012	-0 646	-0 193	-0 290
										0 724	0 975	0 836	0 836	0 349	0 492	0 493	0 909	0 166	0 983	0 166	0 714	0 577
Nitrate + nitrite											0 794	0 924	0 924	-0 137	-0 394	0 612	0 775	0 514	0 679	0 635	0 966	0 978
											0 059	0 009	0 009	0 796	0 440	0 196	0 070	0 297	0 138	0 175	0 002	0 001
Nitrite												0 844	0 844	0 437	0 200	0 551	0 895	0 452	0 887	0 588	0 773	0 687
												0 035	0 035	0 386	0 705	0 257	0 016	0 368	0 019	0 219	0 071	0 132
Total Phosphorous													1 000	0 114	-0 179	0 597	0 923	0 600	0 858	0 593	0 960	0 898
													0 000	0 829	0 735	0 211	0 009	0 208	0 029	0 215	0 002	0 016
Ortho - Phosphate														0 114	-0 179	0 597	0 923	0 600	0 858	0 593	0 960	0 898
														0 829	0 735	0 211	0 009	0 208	0 029	0 215	0 002	0 016
Chloride															0 941	-0 230	0 359	0 181	0 437	-0 239	-0 128	-0 300
															0 005	0 662	0 485	0 732	0 386	0 648	0 809	0 563
Sulphate																-0 426	0 052	-0 136	0 156	-0 363	-0 414	-0 549
																0 399	0 923	0 798	0 768	0 480	0 414	0 260
Total Calcium																	0 670	0 337	0 689	0 920	0 731	0 688
																	0 146	0 513	0 130	0 009	0 099	0 131
Total Magnesium																		0 676	0 983	0 591	0 858	0 728
																		0 141	0 000	0 217	0 029	0 101
Total Potasium																			0 582	0 030	0 586	0 480
																			0 225	0 955	0 222	0 336
Total Sodium																				0 626	0 780	0 633
																				0 183	0 067	0 178
Total Copper																					0 704	0 700
																					0 118	0 122
Total Iron																						0 975
																						0 001
Total Manganese																						

Appendix 9: Correlation coefficients with significance levels highlighted for Autumn Storm parameters from Crystal Creek during 2001.

	Flow	Turbidity	Conductivity	pH	Colour	TDS	TSS	Total N	Ammonia	Nitrate+nitrite	Nitrite	Total P	Ortho-P	Chloride	Sulphate	Ca	Mg	K	Na	Cu	Fe	Mn
Flow		0 5774	0 1289	0 205	0 704	0.07	0 57	0 814	-0 38	0.3471	0 59	0.79	0.591	0 493	0 192	-0 1	-0 1	0 342	0 62	0 504	0.71	0 783
		0 2302	0 8078	0 697	0 118	0.9	0 24	0 049	0.4572	0 5002	0 22	0 06	0 217	0 32	0 716	0 85	0 8	0 507	0 189	0 309	0 11	
Turbidity			0 4592	0.871	0.985	0.72	1	0.937	-0 155	0 6806	0.99	0.94	0.995	-0 298	0.403	0 69	0 67	0.854	0 457	0 768	0.98	0.941
			0 3596	0 024	3E-04	0.11	0	0.006	0.7699	0 1368	0	0	0	0 566	0.428	0 13	0 15	0 03	0 362	0 075	0	
Conductivity				0 322	0 462	0.66	0.45	0.356	0.4223	0 1741	0 37	0 26	0.369	-0.541	0.937	0 7	0 73	0.648	-0 11	0.492	0 38	0 243
				0 534	0 356	0.15	0 38	0 489	0 4041	0 7415	0.47	0 62	0 471	0 268	0 006	0 12	0 1	0 164	0 833	0 321	0 46	
pH					0 796	0 8	0.89	0 677	-0 278	0 5576	0.87	0 72	0.872	-0 425	0 323	0.75	0 74	0 696	0 429	0 457	0.8	0 726
					0 058	0 06	0 02	0 139	0 5933	0 2503	0 02	0 11	0 024	0 401	0 532	0 08	0.09	0 124	0 396	0 363	0 06	
Colour						0 66	0.98	0.976	-0.207	0.6545	0.98	0.97	0.979	-0 163	0 43	0.59	0.56	0.813	0 525	0.763	1	0.967
						0 16	0	9E-04	0 6943	0 1584	0	0	7E-04	0 757	0 395	0.22	0.24	0 049	0 285	0 078	0	
TDS							0 74	0 482	-0.113	0.6572	0 68	0 48	0 682	-0 486	0 594	0.76	0.79	0 583	0 375	0 341	0.62	0 477
							0 09	0 333	0 8316	0.1562	0 14	0 33	0 136	0 329	0 214	0 08	0 06	0 225	0 463	0 509	0 19	
TSS								0 927	-0 213	0 6889	0.99	0.94	0.994	-0 272	0.404	0 68	0 65	0 822	0 506	0 721	0.98	0 935
								0 008	0.6857	0 1301	0	0 01	1E-04	0 603	0 427	0 14	0.16	0 045	0 306	0 106	0	
Total Nitrogen									-0 201	0 6033	0.94	0.99	0.941	-0 039	0 327	0 46	0 42	0 772	0 511	0 798	0.98	0.989
									0.7024	0 2049	0 01	0	0.005	0 942	0 528	0 36	0 41	0 072	0 3	0 057	0	
Ammonia										-0 2206	-0 2	-0 28	-0.208	-0.692	0.209	0 4	0 39	0 359	-0.9	0.416	-0 24	-0 286
										0 6745	0 69	0 59	0 693	0 128	0 691	0 44	0 45	0.485	0 013	0 412	0 64	
Nitrate + nitrite											0 71	0 64	0.707	-0 11	-0.03	0.34	0.34	0.413	0 525	0 471	0 68	0.638
											0 12	0 17	0 116	0 835	0 959	0 51	0 51	0 415	0.285	0 345	0 14	
Nitrite												0.96	1	-0 25	0 312	0.64	0.61	0.818	0 495	0 75	0.99	0 957
												0	0	0 634	0 547	0 17	0 2	0 047	0 319	0 086	0	
Total Phosphorous													0.957	-0 017	0 234	0 44	0.39	0 736	0 561	0 756	0.99	1
													0 003	0 974	0 655	0 39	0 44	0 095	0 247	0 082	0	
Ortho - Phosphate														-0 25	0.312	0.64	0 61	0.818	0 495	0 75	0.99	0.957
														0 634	0 547	0 17	0 2	0 047	0 319	0 086	0	
Chloride															-0 36	-0.88	-0.9	-0 643	0 587	-0 45	-0 13	-0 014
															0.482	0 02	0 02	0 168	0 22	0 368	0 81	
Sulphate																0 58	0.61	0 527	0 021	0.312	0 34	0 219
																0 23	0 2	0 283	0 969	0.547	0.51	
Total Calcium																	1	0 871	-0 18	0 638	0 55	0 431
																	0	0 024	0 727	0 173	0.26	
Total Magnesium																		0.838	-0 17	0.591	0.52	0 39
																		0 037	0 742	0 216	0 29	
Total Potasium																			-0 06	0.916	0 79	0.731
																			0 911	0 01	0 06	
Total Sodium																				-0.08	0 55	0 563
																				0 877	0 26	
Total Copper																					0.76	0 75
																					0 08	
Total Iron																						0 984
Total Manganese																						

Appendix 10: Correlation coefficients with significance levels highlighted for autumn storm physical parameters from Warra and Crystal creeks during 2001.

Warra Creek	Flow	Turbidity	Conductivity	pH
Flow		0.0415	0.6363	-0.5462
		0.8474	0.0008	0.0058
Turbidity			0.3886	0.1756
			0.0606	0.4118
Conductivity				-0.6936
				0.0002
pH				

Crystal creek	Flow	Turbidity	Conductivity	pH
Flow		**0.436**	**0.225**	**0.1259**
		0.0375	**0.3021**	**0.567**
Turbidity			**0.4436**	**0.8382**
			0.034	**0**
Conductivity				**0.4284**
				0.0414
pH				

Appendix 11: Raw data for Warra and Crystal creeks from the autumn storm (11/4 – 13/4) during 2001.

Number	Time	Stage Height mm	Turbidity ntu Warra	Turbidity ntu Crystal	Conductivity uS/cm Warra	Conductivity uS/cm Crystal	pH Warra	pH Crystal	Apparent Colour CU Warra	Apparent Colour CU Crystal	Chloride mg/L Warra	Chloride mg/L Crystal	Sulphate mg/L Warra	Sulphate mg/L Crystal	Ammonia ug-N/L Warra	Ammonia ug-N/L Crystal
1	3:00	0.256	4.1	0.9	43.2	55	4.79	5.56		43		7.8		0.83		21
2	5:00	0.302	1.3	0.9	50	43.4	4.67	5.56	183		8.7		0.78		16	
3	7:00	0.345	1.5	3.1	40	44.5	4.61	5.86	176		8.3		0.83		31	
4	11:00	0.37	6.2	5.3	64	45.2	4.48	5.87	195		8.7		0.98		16	
5	13:00	0.386	11.2	10.2	54	63	4.29	5.86	282	139	8.9	7.8	0.8	0.91	20	16
6	15:00	0.404	8.2	10.2	51	46.4	4.11	5.86								
7	17:00	0.418	5	11.3	50	44.8	4.03	5.96	272		9.3		0.97		21	
8	19:00	0.428	3	10.9	52	43.1	4.01	5.94								
9	21:00	0.438	2.7	8.2	57	42.6	4.05	5.87	248		9.6		1.2		19	
10	23:00	0.681	2.6	9.2	51.8	55	3.97	5.72		142		9.3		0.78		15
11	0:00	0.699	2.1	9.2	58	43.2	3.92	5.72	234		9.8		1.4		16	
12	2:00	0.662	2	3	51.1	59	3.98	5.63		78		10		0.75		21
13	5:00	0.598	2	3	50.6	43.8	3.98	5.63								
14	7:00	0.535	1.8	0.9	50.6	55	4	5.54		63		9.8		0.88		15
15	9:00	0.475	1.8	0.9	57	43	4.02	5.54	211		9.9		1.4		63	
16	11:00	0.424	1.3	0.7	48.6	52	4.13	5.44		48		9.5		0.77		11
17	13:00	0.384	1	0.7	49.3	42.6	4.1	5.44								
18	15:00	0.352	1.2	0.3	48.6	42.3	4.07	5.42								
19	17:00	0.324	1.7	0.2	69	41.9	4.05	5.51	200		9.8		1.6		77	
20	19:00	0.3	1	0.2	48.5	54	4.08	5.56		39		9.1		0.76		16
21	21:00	0.277	1.3	0.2	47.8	42.1	4.1	5.56								
22	23:00	0.259	1.2	0	47.9	41.6	4.11	5.65								
23	0:00	0.244	1.2	0	46.2	68	4.24	5.66		32		9.1		0.75		14
24	3:00	0.23	1		64		4.19		185		9.6		1.4		16	

Number	Nitrate + Nitrite ug-N/L Warra	Nitrate + Nitrite ug-N/L Crystal	Nitrite ug-N/L Warra	Nitrite ug-N/L Crystal	Phosphate ug/P-L Warra	Phosphate ug/P-L Crystal	Total Nitrogen ug/L Warra	Total Nitrogen ug/L Crystal	Total Phosphorous ug/L Warra	Total Phosphorous ug/L Crystal	Total Copper ug/L Warra	Total Copper ug/L Crystal
1		5		2		<2		179		8		10
2	10		5		10		354		10		13	
3	10		5		11		362		11		34	
4	8		4		13		406		13		11	
5	10	6	6	3	16	2	579	360	16	12	12	10
6												
7	12		7		15		642		15		155	
8												
9	11		7		13		590		13		18	
10		6		3		2		451		14		11
11	10		6		12		498		12		13	
12		5		2		<2		322		8		10
13												
14		5		2		<2		231		9		8
15	10		6		11	<2	494		11		9	
16		6		<2		<2		170		8		8
17						<2						
18						<2						
19	9		6		10	<2	458		10		29	
20		6		2		<2		154		8		8
21						<2						
22						<2						
23		5		2		<2		138		8		7
24	10		6		10		354		10		12	

Number	Total Iron ug/L Warra	Total Iron ug/L Crystal	Total Manganese ug/L Warra	Total Manganese ug/L Crystal	Total Calcium mg/L Warra	Total Calcium mg/L Crystal	Total Potassium mg/L Warra	Total Potassium mg/L Crystal	Total Magnesium mg/L Warra	Total Magnesium mg/L Crystal
1		248		6		1.91		0.24		1.43
2	623		17		1.15		0.2		1.09	
3	669		19		1.12		0.19		1.06	
4	641		16		1.06		0.21		1.02	
5	994	897	26	39	1.31	2.28	0.23	0.29	1.28	1.66
6										
7	743		24		1.17		0.25		1.27	
8										
9	695		20		1.24		0.23		1.27	
10		990		56		1.71		0.26		1.3
11	635		16		1.13		0.2		1.2	
12		434		17		1.52		0.2		1.24
13										
14		368		14		1.44		0.16		1.18
15	617		15		1.1		0.26		1.18	
16		293		6		1.46		0.16		1.21
17										
18										
19	600		17		1.1		0.17		1.19	
20		252		6		1.5		0.14		1.22
21										
22										
23		225		7		1.55		0.14		1.23
24	594		15		1.09		0.16		1.1	

Number	Total Sodium mg/L Warra	Total Sodium mg/L Crystal
1		5.05
2	5.33	
3	5.19	
4	5.17	
5	5.68	5.28
6		
7	5.82	
8		
9	5.93	
10		5.31
11	5.72	
12		5.54
13		
14		5.28
15	5.6	
16		5.3
17		
18		
19	5.79	
20		5.25
21		
22		
23		5.24
24	5.4	

Appendix 12: Correlation coefficients with significance levels highlighted for winter storm parameters from Warra Creek during 2001.

Warra Creek	flow	Ammonia	Ca	Chloride	Colour	Conductivity	Cu	Fe	Mg	Mn	Nitrate+nitrite	Nitrite	Total N	Ortho-P	pH	Total P	K	Na	Sulphate	Turbidity
flow		-0 388	0 439	-0.821	0.721	0 423	0 599	0 274	0 463	0 210	0.766	0.872	0 500	-0.449	-0.792	0 100	0.537	0 254	0 404	0 024
		0 302	0 238	0.007	0 028	0 257	0 089	0 475	0 209	0 588	0.016	0 002	0 171	0 225	0 011	0 797	0 136	0.510	0 281	0 951
Ammonia			-0.811	0 461	-0 616	0 304	-0 650	-0.787	-0.808	-0.735	-0 311	-0 391	-0 529	0 586	-0 044	-0 570	-0.854	-0.801	-0 093	-0 604
			0 008	0 212	0 077	0 426	0 058	0 012	0 008	0 024	0 416	0 299	0 143	0 097	0.911	0 109	0 003	0 009	0.812	0 085
Total Calcium				-0 641	0.859	-0 340	0.767	0.958	0.989	0.932	0 616	0 654	0.836	-0.661	0.139	0.777	0.928	0.860	0 055	0.794
				0 063	0 003	0 371	0 016	0 000	0 000	0 000	0 077	0 056	0 005	0.053	0 721	0.014	0 000	0 003	0.888	0.011
Chloride					-0 876	0 101	-0.591	-0 536	-0 633	-0 467	-0.860	-0.966	-0.794	0.668	0 454	-0 484	-0.697	-0 401	-0.113	-0 362
					0 002	0 797	0 094	0 137	0 067	0 205	0 003	0 000	0 011	0 049	0 220	0 187	0 037	0 285	0 771	0.339
Apparent Colour						-0 198	0 610	0.811	0.824	0.785	0.846	0.888	0.951	-0 555	-0 178	0.740	0.788	0 537	-0 057	0.686
						0 610	0 081	0 008	0 006	0 012	0.004	0 001	0 000	0 121	0 646	0.023	0 012	0 136	0 885	0.041
Conductivity							0 169	-0 533	-0 250	-0 544	0.081	0.069	-0.437	0 128	-0.748	-0.752	-0 212	-0 223	0.678	-0.716
							0 663	0 139	0 517	0 130	0 837	0 860	0 240	0 744	0 020	0 020	0 585	0 564	0 045	0.030
Total copper								0 567	0.846	0 498	0 624	0.668	0.440	-0.740	-0 310	0 217	0.877	0.876	0 657	0.231
								0 112	0 004	0 173	0 073	0.049	0.236	0 023	0 418	0 574	0 002	0 002	0 055	0 551
Total Iron									0.912	0.991	0 473	0 517	0.854	-0 515	0.349	0.905	0.821	0.764	-0 180	0.925
									0 001	0 000	0 198	0 154	0 003	0 156	0 357	0 001	0 007	0 017	0.644	0 000
Total Magnesium										0.876	0 630	0 659	0.775	-0.712	0.073	0.686	0.957	0.910	0 189	0.709
										0 002	0 069	0 054	0 014	0.031	0 853	0 041	0 000	0 001	0 626	0.032
Total Manganese											0 442	0 461	0.846	-0.427	0.412	0.920	0.757	0.709	-0 259	0.951
											0 234	0 212	0 004	0.252	0 271	0 000	0 018	0 032	0 501	0 000
Nitrate + Nitrite												0.915	0.749	-0.474	-0 458	0.413	0 659	0 390	0 184	0 327
												0 001	0 020	0.197	0 215	0 269	0 054	0 300	0 635	0.390
Nitrite													0.774	-0.609	-0 512	0.415	0.681	0 413	0 228	0.312
													0 014	0 082	0 159	0 267	0 043	0 270	0 555	0.414
Total Nitrogen														-0.501	0 083	0.881	0.704	0 475	-0 286	0.825
														0 169	0 832	0 002	0 034	0 196	0 455	0.006
Ortho - Phosphate															0.167	-0 301	-0 792	-0.714	-0 352	-0 276
															0.667	0 431	0 011	0 031	0 353	0.473
pH																0 495	-0 075	0 142	-0 572	0.574
																0 175	0 847	0 715	0.108	0.106
Total Phosphorous																	0 587	0 471	-0.533	0.981
																	0 096	0 201	0 140	0.000
Total Potasssium																		0.916	0 295	0.587
																		0 001	0 441	0.096
Total Sodium																			0 399	0.522
																			0 287	0.150
Sulphate																				-0 510
																				0.161
Turbidity																				

Appendix 13: Correlation coefficients with significance levels highlighted for winter storm parameters from Crystal Creek during 2001.

Crystal Creek	flow	Ammonia	Ca	Chloride	Colour	Conductivity	Cu	Fe	Mg	Mn	Nitrate+nitrite	Nitrite	Total N	Ortho-P	pH	Total P	K	Na	Sulphate	Turbidity
flow		-0.860	-0.218	-0.818	0.778	-0.268	-0.543	0 280	-0.334	0.217	0.210	0.768	0.687	0.375	-0 507	0.481	-0.066	-0.431	-0.693	0 497
		0 013	0.638	0.024	0.039	0 561	0.208	0 543	0.464	0 640	0 651	0.044	0.088	0.407	0.246	0.275	0.888	0 334	0.084	0.256
Ammonia			0 274	0.547	-0.451	0.042	0.545	-0.045	0.353	-0 020	-0.405	-0.388	-0.302	0.100	0.420	-0.179	0 136	0 440	0.405	-0.344
			0.552	0.204	0.310	0.929	0 206	0.923	0.438	0.967	0.367	0.390	0 510	0.831	0.348	0 701	0.772	0.323	0.367	0 450
Total Calcium				0.149	0.172	0.341	0.811	0.830	0.984	0.824	0.325	0.086	0 240	0.090	0.262	0.448	0.979	0.754	0.446	0.501
				0.751	0.712	0.455	0 027	0.021	0.000	0.023	0.477	0.855	0.605	0.849	0.571	0 313	0 000	0.050	0 316	0.252
Chloride					-0 714	0.708	0 254	-0.382	0 213	-0.147	0.276	-0.870	-0.727	-0 644	0.782	-0 401	-0.033	0.080	0.473	-0.228
					0.072	0.075	0.582	0.398	0.646	0.754	0.549	0.011	0.064	0 119	0.038	0.372	0.944	0.866	0.283	0.623
Apparent Colour						-0.139	-0.302	0.656	0.012	0.657	0.304	0.948	0.980	0.521	-0.154	0.909	0.278	-0.249	-0.622	0.810
						0.766	0.510	0.110	0.979	0.109	0.508	0 001	0.000	0 231	0 742	0.005	0.547	0.591	0 136	0.027
Conductivity							0.048	0.001	0.294	0.312	0.781	-0.422	-0 246	-0 531	0.863	0.155	0.201	-0.144	0.179	0.436
							0.919	0.998	0.523	0.496	0 038	0.346	0 595	0.220	0.012	0.739	0.666	0.758	0 701	0.328
Total copper								0 500	0.900	0.368	-0 185	-0.242	-0 178	0.106	0.028	-0.082	0.776	0.974	0.712	-0 091
								0 253	0.006	0 416	0.692	0.602	0 703	0.821	0.952	0.862	0.040	0.000	0.073	0 846
Total Iron									0.749	0.930	0.274	0.614	0.718	0.414	-0.064	0.765	0.899	0 526	0.020	0 716
									0.053	0 002	0.553	0.142	0.069	0.356	0.892	0 045	0 006	0 225	0.966	0.071
Total Magnesium										0.712	0.211	-0.041	0.094	0.058	0.215	0 287	0.955	0.848	0.561	0.339
										0.073	0.651	0 930	0.841	0 901	0.643	0.533	0.001	0.016	0.190	0.458
Total Manganese											0.543	0 509	0.683	0 242	0.266	0.852	0.842	0.327	-0.067	0.870
											0.208	0.243	0.091	0 601	0 565	0.015	0.017	0.474	0.887	0.011
Nitrate + Nitrite												0.000	0.174	-0.523	0.575	0.476	0.297	-0.275	-0.082	0.739
												1.000	0 709	0 228	0 177	0.281	0.518	0.551	0 861	0.058
Nitrite													0.966	0.683	-0.394	0.787	0.219	-0.142	-0.576	0.603
													0.000	0.091	0.383	0.036	0 638	0.761	0.176	0.152
Total Nitrogen														0.614	-0.194	0.906	0 345	-0.116	-0 569	0 750
														0.142	0.678	0.005	0 448	0 804	0.182	0.052
Ortho - Phosphate															-0.435	0 375	0 146	0.152	-0.467	0.144
															0 329	0.408	0.754	0.745	0.291	0.758
pH																0.208	0.087	-0.180	0.151	0.332
																0.655	0 854	0.700	0.746	0.467
Total Phosphorous																	0.490	-0.100	-0 399	0.926
																	0.264	0.831	0 375	0 003
Total Potasssium																		0.763	0 398	0 525
																		0.046	0 377	0 226
Total Sodium																			0.693	-0.142
																			0.084	0 761
Sulphate																				-0 346
Turbidity																				

Appendix 14: Correlation coefficients with significance levels highlighted for winter storm physical parameters from Warra and Crystal creeks during 2001.

Warra Creek	flow	Turbidity	pH	Conductivity
flow		**0.1515**	**-0.8312**	**0.2366**
		0.3094	**0**	**0.1093**
Turbidity			**0.3359**	**-0.6839**
			0.021	**0**
pH				**-0.5026**
				0.0003
Conductivity				

Crystal creek	flow	Turbidity	pH	Conductivity
flow		0.4468	-0.704	-0.5373
		0.0019	0	0.0001
Turbidity			0.1862	0.3632
			0.2154	0.0131
pH				0.7892
				0
Conductivity				

Appendix 15: Raw data for Warra and Crystal creeks from the Winter storm (16/9 – 18/9) during 2001.

Sample no.	Time	Stage Height mm	Turbidity ntu Warra	Turbidity ntu Crystal	Conductivity uS/cm Warra	Conductivity uS/cm Crystal	pH Warra	pH Crystal
1	10:00	304	9.1	2	36.5	39.6	5.03	6.23
2	11:00	518	10.2	3.4	36	39.2	4.86	6.19
3	12:00	534	8.5	4.4	36.4	38.4	4.69	6.13
4	13:00	536	12.2	6.2	37.3	38	4.49	6.14
5	14:00	572	11	14.1	37.1	36.9	4.28	6.11
6	15:00	601	6.8	10.1	37	34.3	4.15	6.03
7	16:00	642	6.6	8.1	37.3	32.7	4.11	5.97
8	17:00	657	6	6.2	37.1	31.7	4.04	5.88
9	18:00	644	5.3	5.5	37.5	31.1	3.98	5.86
10	19:00	626	4.7	5.7	37.5	30.8	3.93	5.78
11	20:00	603	4.2	4.6	37.6	30.4	3.93	5.71
12	21:00	582	4.1	4.5	37.5	30	3.92	5.65
13	22:00	574	3.7	4.7	37.7	29.9	3.91	5.59
14	23:00	572	3.4	4.2	37.8	29.7	3.93	5.53
15	0:00	584	3.6	3.1	37.7	29.5	3.89	5.49
16	1:00	597	3.4	2.9	37.8	29.5	3.91	5.53
17	2:00	609	3.4	2.9	38.1	29.6	3.89	5.49
18	3:00	611	3.2	2.6	38.4	29.7	3.88	5.47
19	4:00	599	3.4	2.4	38.4	29.7	3.89	5.47
20	5:00	580	3.1	2.4	38.7	29.7	3.86	5.46
21	6:00	563	3	2.3	38.6	30.2	3.83	5.44
22	7:00	551	3.1	2.7	38.7	30.5	3.85	5.4
23	8:00	538	2.9	2.8	38.8	30.6	3.86	5.43
24	9:00	489	3.2	2	38.6	31.4	3.84	5.43
25	11:30	476	3.1	1.9	38.4	31.1	4.22	5.65
26	12:30	466	2.9	1.8	38.5	31.2	4.21	5.75
27	13:30	453	2.9	1.7	38.6	31.5	4.22	5.77
28	14:30	443	2.9	1.7	38.6	31.4	4.22	5.73
29	15:30	435	2.8	1.5	38.5	31.5	4.19	5.76
30	16:30	420	2.8	1.6	38.4	31.3	4.19	5.76
31	17:30	407	2.7	1.6	38.5	31.5	4.26	5.75
32	18:30	397	2.8	1.5	38.4	31.6	4.25	5.81
33	19:30	385	2.7	1.5	38.3	31.6	4.24	5.82
34	20:30	372	2.6	1.5	38.2	31.5	4.25	5.84
35	21:30	364	2.7	1.5	38.1	31.6	4.28	5.87
36	22:30	356	2.6	1.5	38	31.4	4.31	5.89
37	23:30	347	2.7	1.5	38.1	31.6	4.26	5.89
38	0:30	341	2.5	1.4	38	32	4.28	6.03
39	1:30	335	2.2	1.4	37.9	32.1	4.26	6.01
40	2:30	331	2.3	1.4	37.8	32.2	4.26	6
41	3:30	324	2.3	1.3	37.9	32.3	4.27	6
42	4:30	320	2.1	1.7	37.7	32.7	4.27	5.98
43	5:30	314	2.2	1.3	37.8	32.4	4.3	6
44	6:30	312	2.2	1.3	37.6	32.7	4.27	6
45	7:30	308	2.2	1.3	37.9	32.8	4.28	6
46	8:30	304	2.2	1.2	37.7	33	4.28	6.03
47	9:30	301	2.1	1.2	37.6	33.1	4.3	6.03
48	10:30	298	2.1	1.2	37.7	33	4.31	6.03

Sample no.	Apparent colour CU Warra	Apparent colour CU Crystal	Chloride mg/L Warra	Chloride mg/L Crystal	Sulphate mg/L Warra	Sulphate mg/L Crystal	Ammonia ug-N/L Warra	Ammonia ug-N/L Crystal
1	149	38	7.8	6.4	0.81	0.9	14	5
2	180		7.2		0.67		34	
3								
4	266	61	6.6	6	0.72	0.8	27	4
5	279		6.2		0.69		50	
6		117		5.6		0.76		27
7	250		6.0		0.84		47	
8								
9		108		5.4		0.61		12
10								
11								
12	233		6.1		1.00		53	
13		95		5.2		0.83		9
14								
15								
16								
17								
18								
19		69		5.4		0.73		6
20	209		6.8		1.10		28	
21								
22								
23								
24								
25								
26								
27		52		6.6		0.74		60
28								
29								
30								
31								
32	184		7.0		1.20		98	
33								
34								
35								
36								
37		43		5.9		0.87		32
38								
39	164		7.2		1.00		63	
40								
41								
42								
43								
44								
45								
46								
47		38		6		0.83		55
48	145		7.4		0.52		124	

Sample no.	Nitrate + Nitrite ug-N/L Warra	Nitrate + Nitrite ug-N/L Crystal	Nitrite ug-N/L Warra	Nitrite ug-N/L Crystal	Phosphate ug/P-L Warra	Phosphate ug/P-L Crystal	Total Nitrogen ug/L Warra	Total Nitrogen ug/L Crystal
1	5	8	4	<2	2	2	447	150
2	6		5		3		546	
3								
4	8	8	8	<2	3	<2	712	210
5	11		9		3		756	
6		7		3		2		408
7	9		9		2		677	
8								
9		5		3		2		364
10								
11								
12	9		9		3		591	
13		4		3		2		338
14								
15								
16								
17								
18								
19		4		2		2		267
20	8		7		3		491	
21								
22								
23								
24								
25								
26								
27		4		<2		<2		280
28								
29								
30								
31								
32	8		7		3		497	
33								
34								
35								
36								
37		5		<2		<2		205
38								
39	7		6		3		423	
40								
41								
42								
43								
44								
45								
46								
47		3		<2		2		199
48	6		5		4		432	

Sample no.	Total Phosphorous ug/L Warra	Total Phosphorous ug/L Crystal	Total Copper ug/L Warra	Total Copper ug/L Crystal	Total Iron ug/L Warra	Total Iron ug/L Crystal
1	15	7	4	19	1020	348
2	17		4		1020	
3						
4	19	7	5	9	1310	337
5	19		5		1120	
6		14		13		1210
7	14		5		917	
8						
9		10		5		307
10						
11						
12	12		5		784	
13		9		11		719
14						
15						
16						
17						
18						
19		5		11		538
20	8		5		705	
21						
22						
23						
24						
25						
26						
27		6		8		258
28						
29						
30						
31						
32	8		5		637	
33						
34						
35						
36						
37		5		11		345
38						
39	7		5		612	
40						
41						
42						
43						
44						
45						
46						
47		5		13		335
48	8		2		282	

Sample no.	Total Manganese ug/L Warra	Total Manganese ug/L Crystal	Total Calcium mg/L Warra	Total Calcium mg/L Crystal	Total Potassium mg/L Warra	Total Potassium mg/L Crystal
1	20	15	0.82	1.68	0.35	0.28
2	15		0.88		0.34	
3						
4	22	19	1.13	1.08	0.36	0.21
5	18		1.06		0.38	
6		77		1.74		0.32
7	12		0.95		0.37	
8						
9		10		0.55		0.14
10						
11						
12	9		0.83		0.34	
13		21		1.13		0.24
14						
15						
16						
17						
18						
19		11		1.01		0.22
20	8		0.81		0.35	
21						
22						
23						
24						
25						
26						
27		<5		0.65		0.16
28						
29						
30						
31						
32	7		0.76		0.31	
33						
34						
35						
36						
37		6		1.02		0.21
38						
39	7		0.76		0.31	
40						
41						
42						
43						
44						
45						
46						
47		6		1.14		0.21
48	<5		0.38		0.18	

Sample no.	Total Magnesium mg/L Warra	Total Magnesium mg/L Crystal	Total Sodium mg/L Warra	Total Sodium mg/L Crystal
1	0.82	1.28	5.40	4.31
2	0.88		5.26	
3				
4	1.08	0.8	5.24	2.83
5	1.04		5.04	
6		1.22		4.2
7	0.96		4.94	
8				
9		0.39		1.84
10				
11				
12	0.85		4.71	
13		0.85		3.9
14				
15				
16				
17				
18				
19		0.8		3.89
20	0.86		4.87	
21				
22				
23				
24				
25				
26				
27		0.51		2.58
28				
29				
30				
31				
32	0.83		4.87	
33				
34				
35				
36				
37		0.81		3.79
38				
39	0.82		4.97	
40				
41				
42				
43				
44				
45				
46				
47		0.91		4.05
48	0.42		2.75	